

LECTURES ON TECHNICOLOR

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“Faith” is a fine invention
When Gentlemen can see —
But *Microscopes* are prudent
In an Emergency.

— Emily Dickinson, 1860

LECTURES ON TECHNICOLOR

Refs: K.L., “TC–2000”, Frascati Lectures, hep-ph/0007304;
K.L., “Two Lectures on Technicolor”, L’Ecole de GIF,
hep-ph/0202255;
R.S. Chivukula, Les Houches lectures, hep-ph/9803219;
C.T. Hill and E.H. Simmons, Strong Dynamics Review, soon
on hep-ph;
K.L. and S. Mrenna, “The Updated TCSM”, in Pythia; soon
on hep-ph.

I. Introduction to Technicolor and Extended TC

- (1) Why Technicolor?
- (2) Problems of Higgs Models.
- (3) Technicolor: natural, dynamical EWSB.
- (3) Extended Technicolor: dynamical flavor physics.

II. Extended Technicolor—Problems and Solutions

- (1) Show-stoppers.
- (2) Show-savers.

III. Technicolor Signatures

- (1) Low-scale technicolor.
- (2) The Technicolor Straw-Man Model:
rules; particles; signatures.
- (3) TCSM decay and production rates.
- (4) Experimental searches for TCSM modes.

I. INTRODUCTION TO TC AND ETC

I.1 WHY TECHNICOLOR?

- ELECTROWEAK SYMMETRY BREAKING:

What dynamics are responsible for

$$SU(2)_{EW} \otimes U(1)_{EW} \longrightarrow U(1)_{EM} \quad ??$$

- FLAVOR: What is the origin of quark and lepton flavors?

Why do flavors come in three identical generations?

- FLAVOR SYMMETRY BREAKING:

What is the dynamical origin of the nontrivial quark and lepton masses and mixings?

- ENERGY SCALE of EWSB:

$$2^{-\frac{1}{4}} G_F^{-\frac{1}{2}} = 246 \text{ GeV}$$

NEW PHYSICS MUST OCCUR NEAR THIS ENERGY SCALE!

$$\Lambda_{EW} \simeq 1 \text{ TeV}$$

(cf. $f_\pi = 93 \text{ MeV} \longleftrightarrow \Lambda_{QCD} \simeq 200 \text{ MeV}$; $\alpha_{QCD}(\Lambda_{QCD}) \gtrsim 1$)

- ENERGY SCALE of FLAVOR and FSB is UNKNOWN:

$$\Lambda_{FL} \gtrsim \Lambda_{EW} \simeq 1 \text{ TeV}$$

I.2 THE PROBLEMS OF HIGGS MODELS

→ DYNAMICS of EWSB:

Higgs potential $V(\phi) = \lambda(\phi^\dagger\phi - v^2)^2$ provides
NO DYNAMICAL EXPLANATION FOR EWSB

— i.e., WHY $v = 246 \text{ GeV}$ instead of $v = 0??$

The same question applies to “Theory Space EWSB”
(aka “Dimensional Deconstruction”) a la Arkani-Hamed *et al.*:
WHY those operators and not others in DD?
NO dynamical principle underlies DD!
Essentially DITTO for SUSY!

FUNDAMENTAL ENERGY SCALES MUST
HAVE A DYNAMICAL EXPLANATION!

→ NATURALNESS:

$M_H \simeq \sqrt{2\lambda}v$ and $v = \langle\phi\rangle$ are

QUADRATICALLY UNSTABLE AGAINST
RADIATIVE CORRECTIONS. — Why $M_H, v \ll M_{\text{Pl.}}$?

In SUSY, it’s “Set it and forget it!”

Similarly in DD—which seems to need SUSY!

→ **HIERARCHY:**

WHY NOT $v = M_{\text{GUT}} \simeq 10^{16} \text{ GeV}$ or $M_{\text{Pl.}} \simeq 10^{19} \text{ GeV}$?

In SUSY, it's “Set it and forget it!”

In DD, the hierarchy problem is only slightly less severe.

→ **TRIVIALITY:**

$$\lambda(M) \cong \frac{\lambda(\Lambda)}{1 + \frac{24}{16\pi^2} \lambda(\Lambda) \log \frac{\Lambda}{M}} \implies \lambda(M) \rightarrow 0 \quad \text{as} \quad \Lambda \rightarrow \infty$$

Equivalently, $V(\phi)$ describes an *EFFECTIVE THEORY*, valid for scales $M < \Lambda_\infty$, with the Higgs mass satisfying the triviality bound

$$M_H(\Lambda_\infty) \cong \sqrt{2\lambda(M_H)} v = \frac{2\pi v}{\sqrt{3 \log(\Lambda_\infty/M_H)}}$$

LATTICE: $\Lambda_\infty \gtrsim 2\pi M_H \implies M_H \lesssim 700 \text{ GeV}$

OR ... NEW DYNAMICS NEAR 1 TeV !!

→ **FLAVOR:**

Why are there 3 *identical* quark-lepton generations??

Where do Yukawa couplings $\Gamma_{ij}^d \bar{q}_i L \phi d_j R + \dots$ come from??

Are they *ARBITRARY FREE* parameters put in by hand??

Elementary Higgs models, SUSY, Dimensional Deconstruction \Rightarrow

NO DYNAMICAL UNDERSTANDING of FLAVOR, FSB!

Must we wait for M_{GUT} or M_{Pl} $\ggg 1$ TeV for a solution to the flavor problem?

That's what SUSY wants! DD remains silent—so far.

I.3 TECHNICOLOR—NATURAL EWSB

Based on *well-established precedents: BCS and QCD*

Now, a parenthetical remark:

(

$\left(\begin{array}{c} \text{QCD} \end{array}\right)$

In the standard model of $SU(3)_C \otimes SU(2) \otimes U(1)$:

6 massless flavors of **3_C** quarks:

q_{iL} in $SU(2)$ doublets, q_{iR} in $SU(2)$ singlets

$$\implies G_f = SU(6)_L \otimes SU(6)_R$$

Quark condensates form when α_{QCD} becomes strong:

$$\langle \bar{q}_i q_j \rangle = -\delta_{ij} \Delta_q (= \mathcal{O}(\Lambda_{QCD}^3))$$

$$\implies G_f = SU(6)_L \otimes SU(6)_R \longrightarrow S_f = SU(6)_V$$

$\implies 35 = 6^2 - 1$ MASSLESS 0^- Goldstone bosons π_a

They're $\bar{q}_i q_j$ COMPOSITES, NOT ELEMENTARY!!

3 GBs that couple to the axial parts of the weak $SU(2) \otimes U(1)$ currents get EATEN(!) by W^\pm and Z^0 to produce masses

$$M_W^2 = \frac{3}{2} g^2 f_\pi^2$$

$$M_Z^2 = \frac{3}{2} (g^2 + g'^2) f_\pi^2 \equiv M_W^2 / \cos^2 \theta_W$$

The *RIGHT* ratio, but the *WRONG* size—by 1/1500!

$\left.\right)$

- TC = asymptotically free gauge theory
of MASSLESS fermions T with $\Lambda_{TC} \simeq 0.1\text{--}1.0 \text{ TeV}$.

$\implies T_{iL,R} = (U_i, D_i)_{L,R}$ form N LH–doublets of $SU(2)_{EW}$
and $2N$ RH–singlets.

Assume $SU(3)_C$ –singlets, for now \implies
 $SU(2N)_L \otimes SU(2N)_R$ technifermion flavor symmetry.

\implies **DYNAMICAL EXPLANATION FOR EWSB:**

Just like chiral symmetry breaking in QCD —

At $\alpha_{TC}(\Lambda_{TC}) = \alpha_C = \mathcal{O}(1)$, critical value for χSB :

$SU(2N)_L \otimes SU(2N)_R \longrightarrow SU(2N)_V$:

$$\langle \bar{U}_{iL} U_{jR} \rangle = \langle \bar{D}_{iL} D_{jR} \rangle = -\delta_{ij} \Delta_T (= \mathcal{O}(\Lambda_{TC}^3))$$

$$\implies 4N^2 - 1 \text{ GBs} \equiv \pi_T$$

$$\Lambda_{TC} \sim F_T = F_\pi / \sqrt{N}$$

$$\implies M_W^2 = \frac{1}{2} g^2 N F_T^2$$

$$M_Z^2 = \frac{1}{2} (g^2 + g'^2) N F_T^2 \equiv M_W^2 / \cos^2 \theta_W \quad (\text{to } \mathcal{O}(\alpha))$$

\implies NATURAL:

$$\Lambda_{EW} \equiv \Lambda_{\chi SB} \sim F_T \sim \Lambda_{TC} \sim M_{\text{techni}} \quad \text{at } \alpha_{TC}(\Lambda_{TC}) = \mathcal{O}(1)$$

\implies HIERARCHICAL:

Logarithmic running from

$$\alpha_{TC}(M_{\text{GUT}}) \ll 1 \text{ to } \alpha_{TC}(\Lambda_{TC}) \sim 1$$

$$\implies \Lambda_{TC} \ll M_{\text{GUT}}.$$

\implies NONTRIVIAL:

$$\beta(\alpha_{TC}) < 0 \implies \alpha_{TC}(M) \text{ has no Landau pole at } M > 0.$$

No other EWSB scenario is so simple, elegant, plausible!!

But...FLAVOR and FSB—are NOT addressed by TC alone!

TECHNIHADRONS

Assume N doublets $U_{iL,R}, D_{iL,R} \in \mathbf{N}_{\mathbf{T}\mathbf{C}}$ of $SU(N_{TC})$ and $SU(3)_C$ singlets.

- $\chi SB \implies 4N^2 - 1$ MASSLESS Goldstone bosons π_T , decay constant F_T ;
3 become W_L^\pm, Z_L^0 via the Higgs mechanism.
How do the others get mass?? (FSB again!)
- $4N^2 \rho_T, \omega_T$ decaying to $\geq 2 \pi_T$.
- Other technimesons and baryons.
- A simple phenomeology will be discussed later...
)

I.4 EXTENDED TECHNICOLOR (ETC) — A SCENARIO FOR FLAVOR PHYSICS

- *WHY EXTENDED TECHNICOLOR?*
 - Technicolor (and color) by itself leaves too much chiral symmetry unbroken.
 - Explicit breaking of q, ℓ chiral symmetries — required to give *hard* q, ℓ masses and avoid massless Goldstone bosons — π, K, η, \dots
 - Explicit breaking of technifermion chiral symmetries — required to give hard masses to T_i and avoid Goldstone technipions π_T (NO AXIONS!)

- THE STRUCTURE OF ETC INTERACTIONS

\implies ETC = gauge interaction of MASSLESS T_i, q_a, ℓ_a

$$\underline{G_{ETC} \supset SU(N_{TC}) \otimes SU(3)_C \otimes \text{Flavor}}$$

$\implies G_{ETC} \rightarrow SU(N_{TC}) \otimes SU(3)_C$ at $M_{ETC} \gg \Lambda_{TC} \sim 1 \text{ TeV}$
explicitly breaking ALL global flavor symmetries.

$\implies q, \ell$ hard masses; π_T masses:

The KEY Equations of ETC:

$$m_q, m_\ell, m_T(M_{ETC}) \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{ETC}$$

$$F_T^2 M_{\pi_T}^2 \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T\bar{T}T \rangle_{ETC}$$

$$\langle \bar{T}T \rangle_{ETC} = \langle \bar{T}T \rangle_{TC} \exp \left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

↑

$$\sim \underline{\underline{4\pi F_T^3}}$$

$$\gamma_m(\mu) = \frac{3C_2(N_{TC}) \alpha_{TC}(\mu)}{2\pi} + \dots \equiv \frac{3(N_{TC}^2 - 1) \alpha_{TC}(\mu)}{4\pi N_{TC}} + \dots$$

- Estimate M_{ETC} for $m_q = 1 \text{ GeV}$ (N technidoublets):
ASSUME TC is QCD-like — precociously asymptotically free with α_{TC} decreasing rapidly above Λ_{TC} :

$$\Lambda_{ETC} \equiv \frac{M_{ETC}}{g_{ETC}} \simeq \sqrt{\frac{4\pi F_\pi^3}{m_q N^{3/2}}} \simeq \frac{14 \text{ TeV}}{N^{3/4}}$$

- ETC contribution to π_T mass:

$$F_T^2 M_{\pi_T}^2 \simeq m_T(M_{ETC}) \langle \bar{T}T \rangle_{ETC}$$

$$\implies M_{\pi_T} \simeq \frac{40 \text{ GeV}}{N^{1/4}} \quad (\text{for } m_T(M_{ETC}) = 1 \text{ GeV})$$

ALL contributions to M_{π_T} add in quadrature.

- Comment on ETC scales: Hierarchy? Tumbling?
- Comment on $m_t > 100 \text{ GeV} \Rightarrow (?) \Lambda_{ETC} \sim 1 \text{ TeV} \sim \Lambda_{TC}$
- What breaks ETC?
Is it turtles all the way down?

II. ETC—PROBLEMS AND SOLUTIONS

II.1 SHOW-STOPPERS (What they complain about.)

→ **FLAVOR CHANGING NEUTRAL CURRENTS**

- Generic ETC models with *realistic* m_q -matrices have FCNC involving mass eigenstate q and/or ℓ :

$$[q^\dagger T, T^\dagger q'] = q^\dagger q' \implies \frac{g_{ETC}^2 V_{sd}^2}{M_{ETC}^2} \bar{s}\Gamma^\mu d \bar{s}\Gamma'_\mu d + \dots$$

NO satisfactory GIM mechanism eliminates these FCNC.

- $|\Delta S| = 2$ FCNC \implies most stringent constraints on ETC:

$$\Delta M_{K^0} = 3.5 \times 10^{-18} \text{ TeV} \implies \frac{M_{ETC}}{g_{ETC} \sqrt{\text{Re}(V_{sd}^2)}} \gtrsim 1300 \text{ TeV}$$

$$|\epsilon| = 2.3 \times 10^{-3} \implies \frac{M_{ETC}}{g_{ETC} \sqrt{\text{Im}(V_{sd}^2)}} \gtrsim 16,000 \text{ TeV}$$

Scaling condensates from QCD (for $\gamma_m \ll 1$)

$$\implies m_{q,\ell,T}(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2} \langle \bar{T}T \rangle_{ETC} \lesssim \frac{0.1 \text{ MeV}}{|V_{sd}|^2 N^{3/2}}$$

$$\implies M_{\pi_T} \simeq \sqrt{\frac{g_{ETC}^2}{2M_{ETC}^2} \frac{\langle \bar{T}T \rangle_{ETC}^2}{F_T^2}} \lesssim \frac{0.4 \text{ GeV}}{|V_{sd}| N}$$

→ PRECISION ELECTROWEAK TESTS

- “*Oblique*” correction factor S —

ASSUMING all new physics scales such as $\Lambda_{TC} \gg M_{W,Z}$:

$$S = 16\pi \frac{d}{dq^2} [\Pi_{33}(q^2) - \Pi_{3Q}(q^2)]_{q^2=0} \equiv 16\pi [\Pi'_{33}(0) - \Pi'_{3Q}(0)]$$

Experimental limit (PDG):

$$S = -0.07 (-0.09) \pm 0.11 \text{ for } M_H = 100 (300) \text{ GeV.}$$

- ESTIMATES OF TC CONTRIBUTIONS TO S

ASSUME TC is QCD-like:

- Spectrum of hadrons scaled from QCD.
- Precocious asymptotic freedom
 - ⇒ rapid convergence of spectral function integrals.
- Vector-meson dominance (VMD) of spectral functions.
- Chiral perturbation theory accurate for technipions.
- *Peskin & Takeuchi*, e.g.: Use QCD as analog computer—
VMD, spectral function sum rules:

$$S = 4\pi \left(1 + \frac{M_{\rho_T}^2}{M_{a_{1T}}^2} \right) \frac{F_T^2}{M_{\rho_T}^2} \simeq 0.25 \frac{N_{TC}}{3}$$

→ TOP QUARK MASS

- $m_t \simeq 175 \text{ GeV}$
 $\implies \Lambda_{ETC} \simeq 0.4/N^{3/4} \text{ TeV} = \mathcal{O}(\Lambda_{TC}), \mathcal{O}(m_t) !!$
(Note: FCNC on 3rd generation are less constraining.)
- ⇒ Or — unnatural fine-tuning of α_{ETC} to $\mathcal{O}(m_t/M_{ETC})$.
- $m_t \gg m_b \implies \underline{\text{large}}$ weak isospin breaking:
- ⇒ Trouble with $\rho = M_W/M_Z \cos \theta_W = 1$, $Z^0 \rightarrow \bar{b}b$, etc.

II.2 SHOW-SAVERS (What they don't tell you.)

→ WALKING TECHNICOLOR

- *THE BASIC IDEA*

The KEY Equations of ETC — Again:

$$m_q, m_\ell, m_T(M_{ETC}) \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{ETC}$$
$$\langle \bar{T}T \rangle_{ETC} = \langle \bar{T}T \rangle_{TC} \exp \left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

If TC = scaled-up QCD,

$$\gamma_m(\mu) \approx \frac{3C_2(N_{TC})\alpha_{TC}(\mu)}{2\pi} \ll 1$$

$$\implies \langle \bar{T}T \rangle_{ETC} \approx \langle \bar{T}T \rangle_{TC}$$

CAN γ_m BE LARGE — ENHANCING $\langle \bar{T}T \rangle_{ETC}/\langle \bar{T}T \rangle_{TC}$?

YES!

- Suppose $\alpha_{TC}(\mu) \simeq \text{constant}$ ($\beta(\alpha_{TC}) = \frac{d\alpha_{TC}(\mu)}{d\log(\mu)} \ll 1$).
Then the anomalous dimension γ_m of $\bar{T}T$ is given approximately by:

$$\gamma_m(\mu) = 1 - \sqrt{1 - \alpha_{TC}(\mu)/\alpha_C}; \quad \alpha_C = \pi/3C_2(N_{TC})$$

$$\rightarrow \frac{3C_2(N_{TC}))\alpha_{TC}(\mu)}{2\pi} \quad \text{for } \alpha_{TC}(\mu) \ll 1$$

- This approximation suggests χ SB occurs *iff*

$$\alpha_{TC} \geq \alpha_C = \pi/3C_2(R)$$

At the χ SB scale Λ_{TC} ,

$$\alpha_{TC}(\Lambda_{TC}) = \alpha_C$$

$$\gamma_m(\Lambda_{TC}) = 1$$

$\gamma_m = 1$ is the signal for χ SB

- To keep γ_m large ...

$$\begin{aligned}\beta(\alpha_{TC}(\mu)) &\simeq 0 \text{ for } \mu > \Lambda_{TC} \\ \implies \alpha_{TC}(\mu) &\simeq \alpha_C \implies \gamma_m(\mu) \simeq 1\end{aligned}$$

HOW?

One simple way: make # doublets $N \gg 1$

$\implies F_T \ll F_\pi, \Lambda_{TC} \ll 1 \text{ TeV}$ (say $F_T \sim \Lambda_{TC} \sim 100 \text{ GeV}$).

i.e., Low-Scale Technicolor!! — See below.

TC is a WALKING gauge theory.

$\implies \underline{\text{CONSEQUENCES OF WALKING TECHNICOLOR}}$

- In extreme walking limit (*problematic!*), $\gamma_m = 1$ up to M_{ETC}

$$\implies \langle \bar{T}T \rangle_{ETC} \simeq \frac{M_{ETC}}{\Lambda_{TC}} \times \langle \bar{T}T \rangle_{TC}$$

$$\implies m_{q,\ell}(M_{ETC}) \simeq \frac{4\pi\alpha_{ETC}\langle \bar{T}T \rangle_{TC}}{M_{ETC}\Lambda_{TC}} \simeq \frac{16\pi^2 F_\pi^2 \alpha_{ETC}}{NM_{ETC}}$$

$$\Rightarrow M_{ETC} = (70 \text{ TeV} - 4 \times 10^5 \text{ TeV}) \times \left(\frac{10}{N} \frac{\alpha_{ETC}}{0.75} \frac{F_T}{\Lambda_{TC}} \right)$$

for $m_q = 5 \text{ GeV} - 1 \text{ MeV}$

$$\implies M_{\pi_T} \simeq \underbrace{\sqrt{1.5\pi} 4\pi F_\pi}_{7(!) \text{ TeV}} \left(\frac{F_T}{\Lambda_{TC}} \right) \sqrt{\frac{\alpha_{ETC}}{0.75N}}$$

$\dots \pi_T$ may NOT be pseudo-Goldstone bosons,
i.e., chiral perturbation theory may break down in walking TC.

In any case, the M_{π_T} are significantly enhanced!

→ S in walking technicolor

- Spectral integrals in $\Pi(q^2)$ —calculation of S converge much slower in a walking gauge theory than in QCD.
- Spectrum of ρ_T , a_{1T} very different from QCD—a tower of (narrow??) resonances up to $\sim M_{ETC}$
⇒ spectral integrals not dominated by just the lowest-lying resonances.
- How to justify scaling arguments from QCD?

Large- N_{TC} arguments break down when N is also large.

⇒ S cannot be reliably estimated without WTC data!!

(The same was true of QCD!!)

→ **TOPCOLOR-ASSISTED TECHNICOLOR (TC2)**

- **Topcolor** = *STRONG* interaction at 1 TeV of third generation (especially quarks).
- *Dynamically* generate large m_t (and condensate $\langle \bar{t}t \rangle$), but *not* m_b —*HOW??*

⇒ “Simplest” TC2 scheme ··· (a picture)

- $\langle \bar{t}t \rangle \neq 0$ produces 3 massless *top-pions* $\pi_t^{\pm,0}$ with $F_t \sim 70 \text{ GeV} \ll F_\pi \implies$ small breaking of $\rho = 1$.
- $m_t^{ETC} \simeq 5 \text{ GeV}$ required to produce $M_{\pi_t} \gtrsim m_t$, preventing $t \rightarrow \pi_t^+ b$.
- Quark, lepton masses;
mixing between generations 1,2 and 3;
 $\bar{B}_d^0 - B_d^0$ mixing constraint; etc., etc.

⇒ $N \sim 10$ (!) T -doublets

Another Variant: The TOP SEESAW

- EW singlet (or vectorial) fermion χ has *hard* Dirac mass $M_\chi \simeq 4 \text{ TeV}$.
- $\langle \bar{t}_L \chi_R \rangle \simeq 700 \text{ GeV} \implies \text{composite Higgs } H \sim (\bar{t}_L, \bar{b}_L) \chi_R$ with $I = \frac{1}{2}$ and $\langle H^0 \rangle = 246 \text{ GeV}$.
- χ seesaw-mixes with t — $M_{\chi_L, t_R} \simeq 1 \text{ TeV}$ —to produce

$$m_t \simeq \frac{700 \text{ GeV} \times 1 \text{ TeV}}{4 \text{ TeV}} \simeq 175 \text{ GeV}$$

- A similar mechanism is used in DD to give $m_t \simeq 175 \text{ GeV}$.

III. TECHNICOLOR SIGNATURES

III.1 LOW-SCALE TECHNICOLOR

- Walking TC ($\beta(\alpha_{TC}) \simeq 0$ from Λ_{TC} to $\sim M_{ETC}$)
 $\implies N \gg 1$.

- TC2 phenomenology $\implies N \gg 1$.

\implies MANY π_T , with decay constant $F_T = F_\pi/\sqrt{N} \lesssim 100 \text{ GeV}$
 $M_{\pi_T} \sim 100 \text{ GeV and up??}$

$\implies \Lambda_{TC} \sim F_T \ll 1 \text{ TeV, } \implies$ MANY ρ_T, ω_T
 $M_{\rho_T}, M_{\omega_T} \sim 200 \text{ GeV and up!!}$

We'll see next that the most promising signals are

$\rho_T \rightarrow W\pi_T; \gamma\pi_T; \ell^+\ell^-$ with $\pi_T \rightarrow \bar{b}b$ or $\bar{b}c$.

$\omega_T \rightarrow \gamma\pi_T; \ell^+\ell^-$

\implies TC may be accessible at the TEVATRON COLLIDER!

...and certainly at the LHC!

III.2 TECHNICOLOR STRAW-MAN MODEL

(Color Singlet Sector)

- **WTC** $\implies M_{\rho_T}, M_{\omega_T} \lesssim 2M_{\pi_T}$
 $\implies \rho_T \rightarrow \pi_T \pi_T, \omega_T \rightarrow \pi_T \pi_T \pi_T$ probably CLOSED!

How do ρ_T, ω_T decay?

Adopt the TCSM GROUND RULES:

- Lightest (T_U, T_D) are color-singlets.
 - (T_U, T_D) -isospin breaking is small;
electric charges $Q_U, Q_D = Q_U - 1$.
 - Consider bound states of lightest (T_U, T_D) IN ISOLATION:
 $\rho_T^{\pm,0}(I=1); \quad \omega_T^0(I=0)$ with $M_{\rho_T} \cong M_{\omega_T}$
 $\Pi_T^{\pm,0}(I=1) = \pi_T^{\pm,0} \cos \chi + W_L^{\pm,0} \sin \chi$ with $\sin \chi = \frac{F_T}{F_\pi} \ll 1$
 $\Pi_T'^0(I=0) = \pi_T'^0 \cos \chi' + \dots$ with $\cos \chi' \simeq \cos \chi ??$
 $W_L^{\pm,0}$ = isotriplet of longitudinal EW bosons.
 - ETC gives Higgs-like coupling of π_T to $\bar{f}f'$ \implies
 - $\pi_T^+ \rightarrow c\bar{b}$ or $c\bar{s}$ or even $\tau^+ \nu_\tau$
 - $\pi_T^0 \rightarrow b\bar{b}$ and, perhaps $c\bar{c}, \tau^+ \tau^-$
 - $\pi_T^{0'} \rightarrow gg, b\bar{b}, c\bar{c}, \tau^+ \tau^-$
 - π_T^0 and $\pi_T^{0'}$ may mix and share decay modes.
- \implies Premium on heavy-flavor ID!

- ρ_T and ω_T Decay Modes:

Consider technihadrons within Tevatron's (& LEP's?) reach:

$$M_{\rho_T} \simeq M_{\omega_T} \sim 200\text{--}300 \text{ GeV}, M_{\pi_T} \lesssim 200 \text{ GeV}.$$

- $\rho_T \rightarrow \Pi_T \Pi_T$ becomes

$$\rho_T \rightarrow \cos^2 \chi (\pi_T \pi_T) + 2 \sin \chi \cos \chi (W_L \pi_T) + \sin^2 \chi (W_L W_L)$$

→ *Competition* between $\sin \chi (\sim 1/3?)$ and phase space —
both suppress $\Gamma(\rho_T)$ and make $W \pi_T$ important.

- ALL $\omega_T \rightarrow \Pi_T \Pi_T \Pi_T$ modes are closed for $M_{\omega_T} \lesssim 300 \text{ GeV} !!$

→ Electroweak decay modes are competitive!!

$$\mathcal{O}(\alpha) : \rho_T, \omega_T \rightarrow G \pi_T \quad (G = \text{"transverse"} \gamma, W^\pm, Z^0)$$

$$\mathcal{O}(\alpha^2) : \rho_T, \omega_T \rightarrow \bar{f} f' \quad (f = \ell^\pm, \nu_\ell; q = u, d, s, c, b)$$

⇒ ρ_T, ω_T are **VERY NARROW**

$$\Gamma(\rho_T) \sim 1 \text{ GeV}, \quad \Gamma(\omega_T) \sim 0.1 \text{ GeV}$$

V_T Decay Mode	$V(V_T \rightarrow G\pi_T) \times M_V/e$	$A(V_T \rightarrow G\pi_T) \times M_A/\epsilon$
$\omega_T \rightarrow \gamma\pi_T^0$	$\cos \chi$	0
	$(Q_U + Q_D) \cos \chi'$	0
	$\cos \chi \cot 2\theta_W$	0
	$-(Q_U + Q_D) \cos \chi' \tan \theta_W$	0
	$\cos \chi / (2 \sin \theta_W)$	0
$\rho_T^0 \rightarrow \gamma\pi_T^0$	$(Q_U + Q_D) \cos \chi$	0
	$\cos \chi'$	0
	$-(Q_U + Q_D) \cos \chi \tan \theta_W$	0
	$\cos \chi' \cot 2\theta_W$	0
	0	$\pm \cos \chi / (2 \sin \theta_W)$
$\rho_T^\pm \rightarrow \gamma\pi_T^\pm$	$(Q_U + Q_D) \cos \chi$	0
	$-(Q_U + Q_D) \cos \chi \tan \theta_W$	$\pm \cos \chi / \sin 2\theta_W$
	0	$\mp \cos \chi / (2 \sin \theta_W)$
	$\cos \chi' / (2 \sin \theta_W)$	0

Relative vector and axial vector amplitudes for $V_T \rightarrow G\pi_T$ for $V_T = \rho_T, \omega_T$ and G a transverse electroweak boson, γ, Z^0, W^\pm . Decay rates are suppressed by $1/M_{V,A}^2$ where $M_{V,A} = \mathcal{O}(\Lambda_{TC})$ are TC mass parameters.

III.3 TCSM PLOTS

1. $\Gamma(V_T = \rho_T, \omega_T)$ for default TCSM and Run II parameters:

$$N_{TC} = 4, \quad \sin \chi = 1/\sqrt{N} = 1/3 = \sin \chi',$$

$$Q_U = Q_D + 1 = \frac{4}{3},$$

$$M_{\rho_T} = M_{\omega_T} = 210 \text{ GeV}, \quad M_{\pi_T} = M_{\pi_T^{0'}} = 110 \text{ GeV},$$

$$M_V = M_A = 200 \text{ GeV};$$

$\bar{p}p$ collisions at $\sqrt{s} = 2 \text{ TeV}$

2. $\sigma(V_T \rightarrow \gamma\pi_T)$ for default parameters.
3. $\sigma(V_T \rightarrow W\pi_T, Z\pi_T, \pi_T\pi_T)$ for default parameters.
4. $\sigma(V_T \rightarrow e^+e^-)$ for default parameters, except $M_V = 100 \text{ GeV}$; M_{ω_T} is varied.
5. $\sigma(V_T \rightarrow e^+e^-)$ for default parameters, except $M_V = 500 \text{ GeV}$; M_{ω_T} is varied.
6. $\sigma(\rho_T^\pm \rightarrow \ell^\pm\nu)$ for default parameters, except $M_V = 100 \text{ GeV}$ and 500 GeV .
7. $\Gamma(V_T = \rho_T, \omega_T)$ for default TCSM parameters, except $Q_U + Q_D = 0$.

8. $\sigma(V_T \rightarrow \gamma\pi_T, W\pi_T, Z\pi_T, \pi_T\pi_T)$ for default parameters, except $Q_U + Q_D = 0$.
9. $\sigma(V_T \rightarrow e^+e^-)$ for default parameters, except $M_V = 100$ GeV and 500 GeV and $Q_U + Q_D = 0$.
10. $\Gamma(V_T = \rho_T, \omega_T)$ for default TCSM parameters, except $M_{\pi_T} = 100$ GeV.
11. $\sigma(V_T \rightarrow \gamma\pi_T)$ for default parameters.
12. $\sigma(V_T \rightarrow W\pi_T, Z\pi_T, \pi_T\pi_T)$ for default parameters, except $M_{\pi_T} = 100$ GeV.
13. $\sigma(V_T \rightarrow e^+e^-)$ for default parameters, except $M_V = 100$ GeV and $M_{\pi_T} = 100$ GeV; M_{ω_T} is varied.
14. $\sigma(V_T \rightarrow e^+e^-)$ for default parameters, except $M_V = 500$ GeV and $M_{\pi_T} = 100$ GeV; M_{ω_T} is varied.

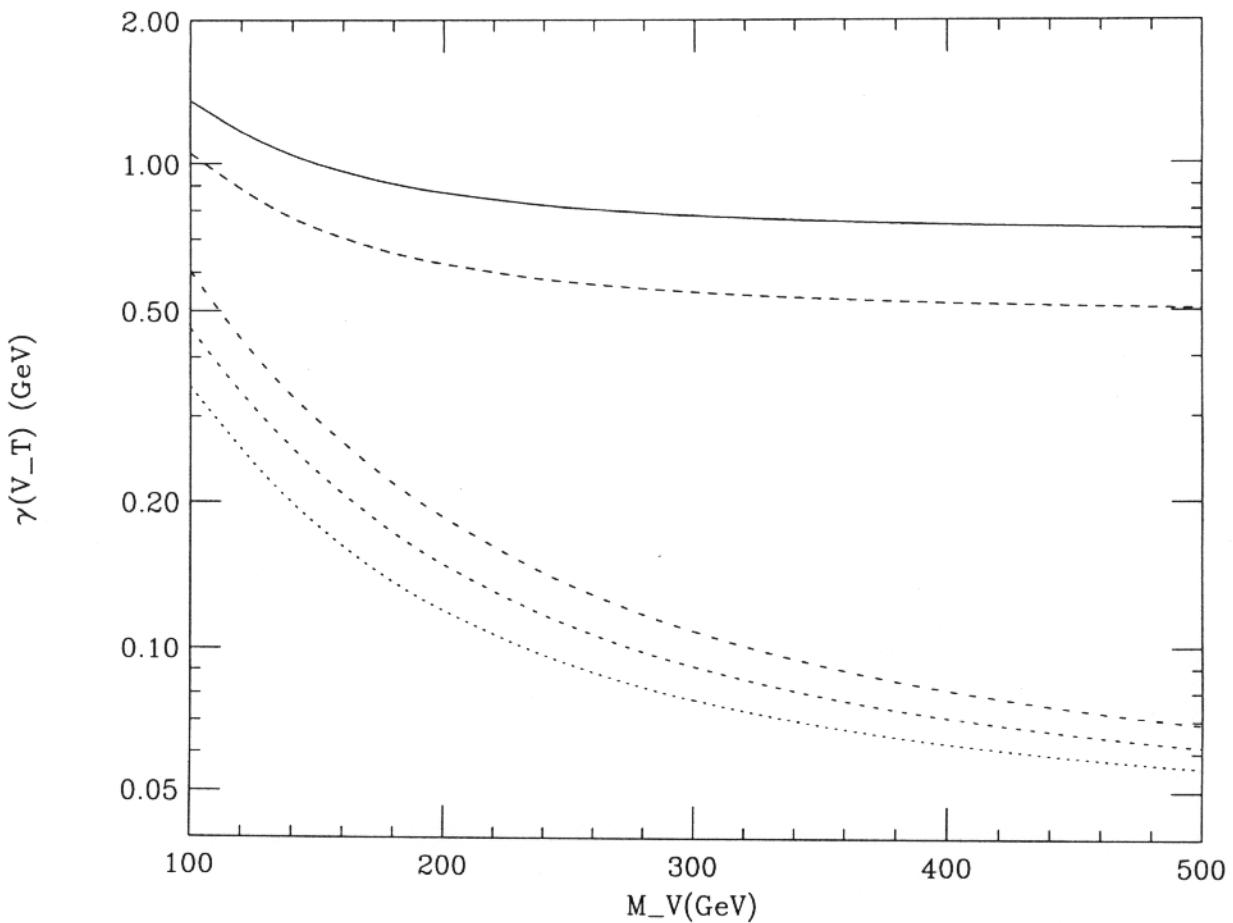


Figure 1: Technivector meson decay rates versus $M_V = M_A$ for ρ_T^0 (solid curve) and ρ_T^\pm (long-dashed) with $M_{\rho_T} = 210$ GeV, and ω_T with $M_{\omega_T} = 200$ (lower dotted), 210 (lower short-dashed), and 220 GeV (lower medium-dashed); $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 110$ GeV.

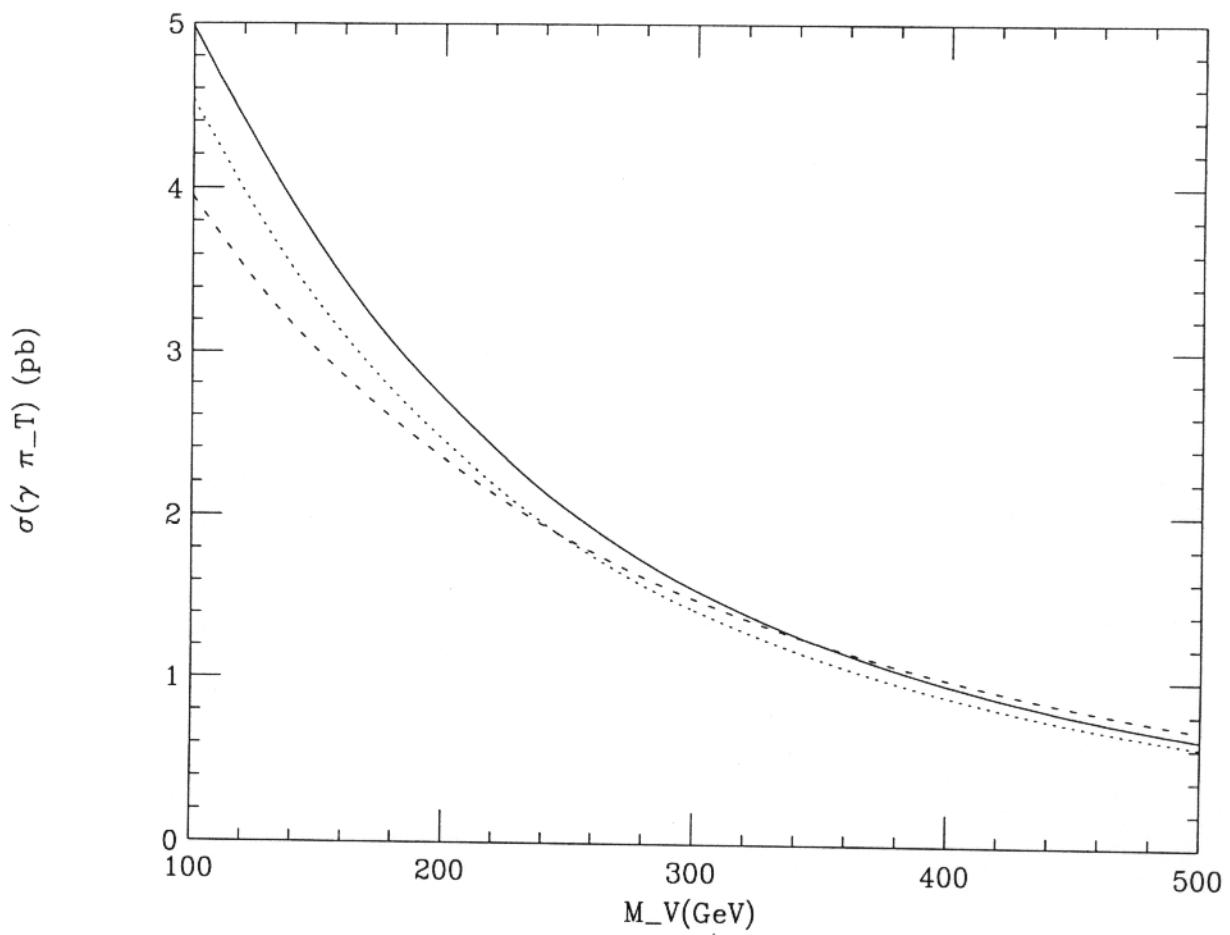


Figure 2: Production rates in $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV for the sum of ω_T , ρ_T^0 , $\rho_T^\pm \rightarrow \gamma\pi_T$ versus M_V , for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (dotted curve), 210 (solid), and 220 GeV (short-dashed); $Q_U + Q_D = 5/3$, and $M_{\pi_T} = 110$ GeV.

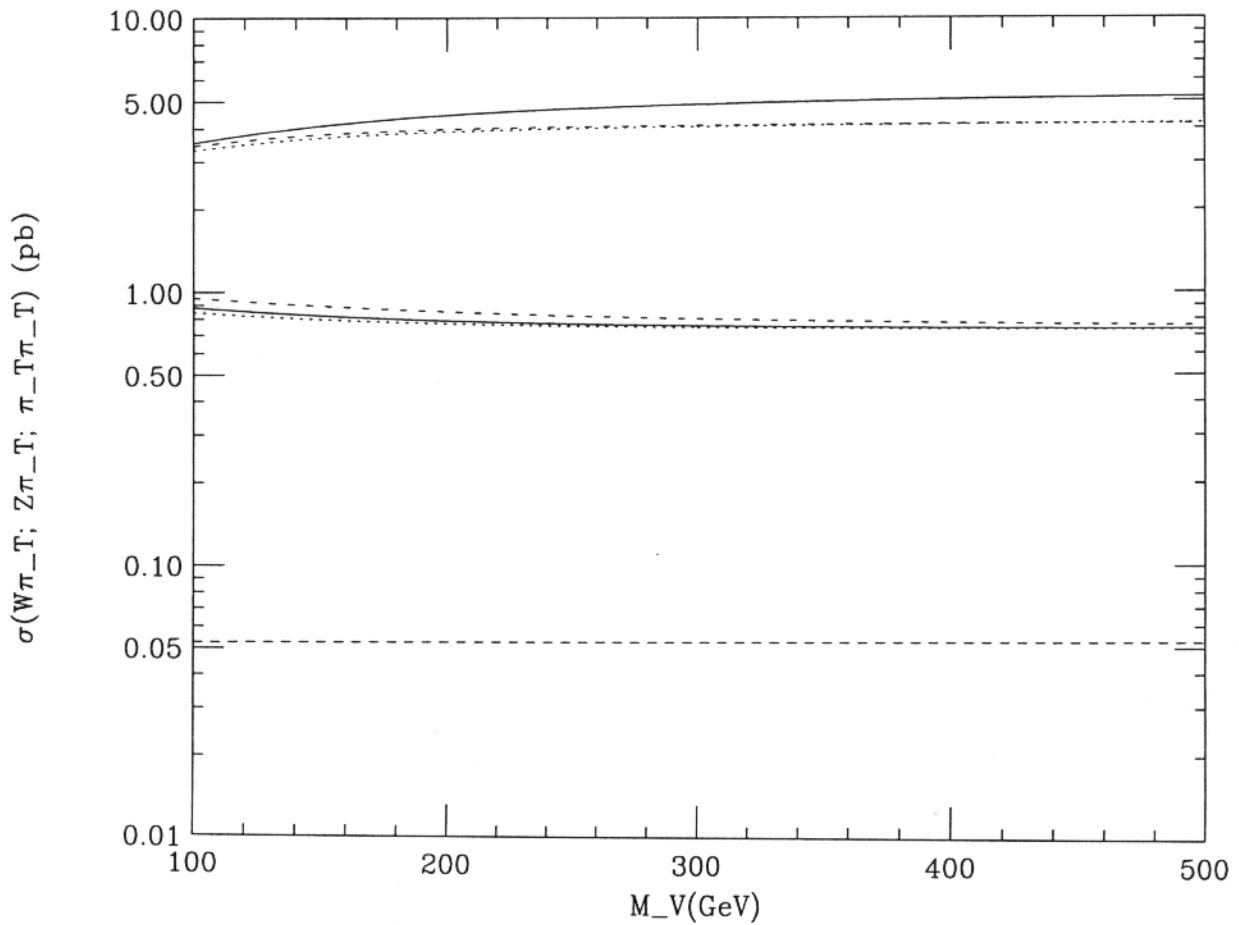


Figure 3: Production rates for ω_T , ρ_T^0 , $\rho_T^\pm \rightarrow W\pi_T$ (upper curves) and $Z\pi_T$ (lower curves) versus M_V , for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (dotted curve), 210 (solid), and 220 GeV (short-dashed); $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 110$ GeV. Also shown is $\sigma(\rho_T \rightarrow \pi_T\pi_T)$ (lowest dashed curve).

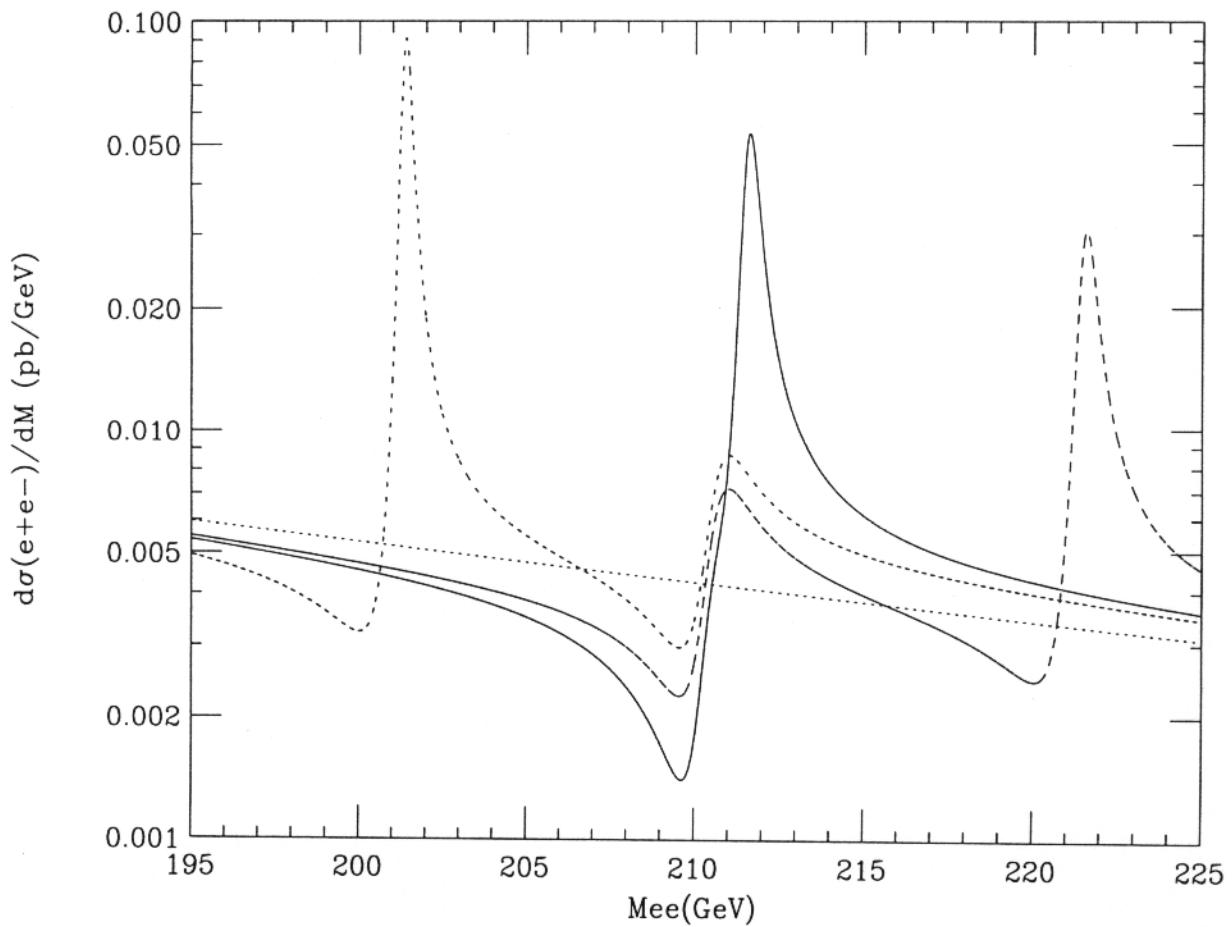


Figure 4: Invariant mass distributions for $\omega_T, \rho_T^0 \rightarrow e^+e^-$ for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (short-dashed curve), 210 (solid), and 220 GeV (long-dashed); $M_V = 100$ GeV. The standard model background is the sloping dotted line. $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 110$ GeV.

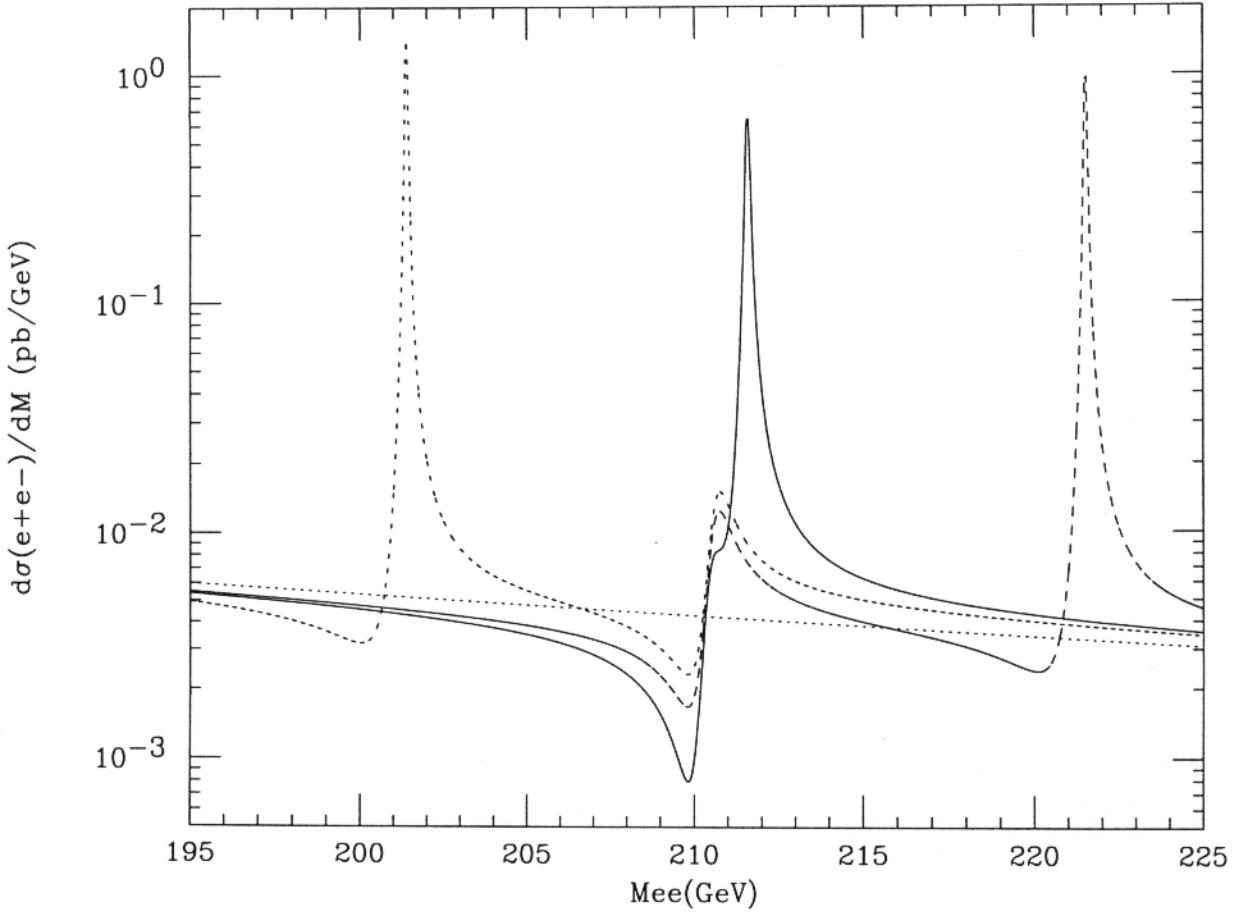


Figure 5: Invariant mass distributions for $\omega_T, \rho_T^0 \rightarrow e^+ e^-$ for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (short-dashed curve), 210 (solid), and 220 GeV (long-dashed); $M_V = 500$ GeV. The standard model background is the sloping dotted line. $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 110$ GeV.

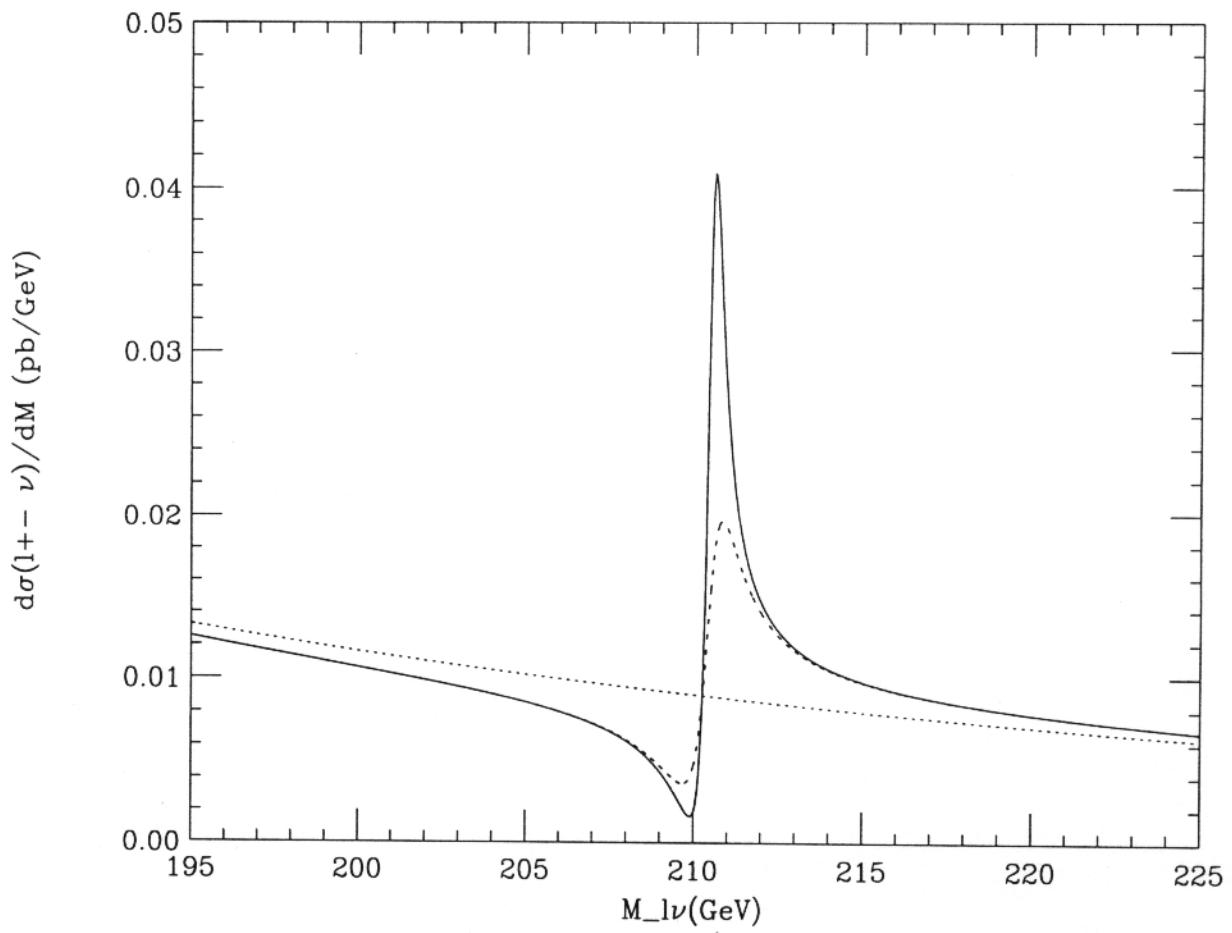


Figure 6: Invariant mass distributions for $\rho_T^\pm \rightarrow \ell^\pm \nu$ for $M_{\rho_T} = 210$ GeV and $M_V = 100$ GeV (dashed curve) and 500 GeV (solid); The standard model background is the sloping dotted line. $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 110$ GeV.

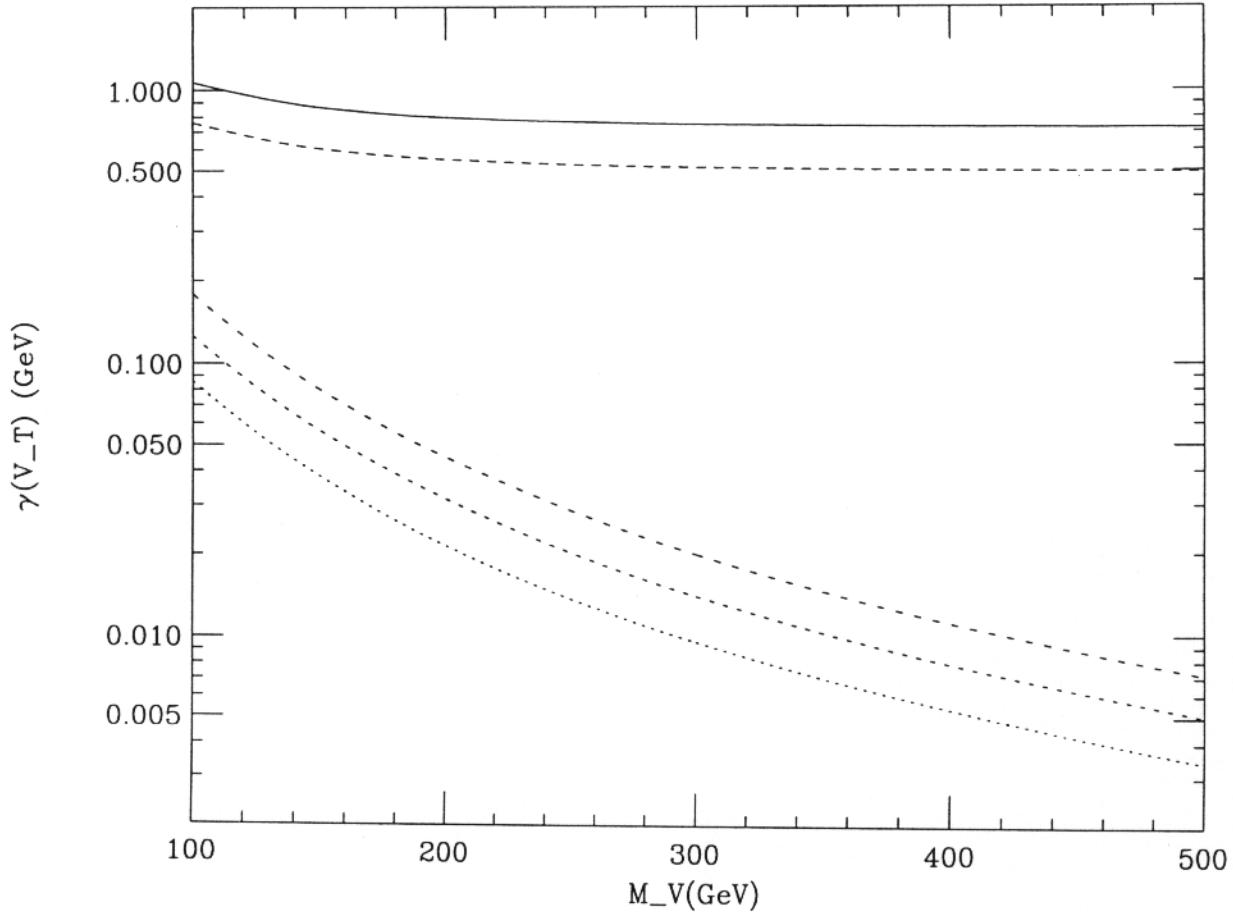


Figure 7: Technivector meson decay rates versus $M_V = M_A$ for ρ_T^0 (solid curve) and ρ_T^\pm (long-dashed) with $M_{\rho_T} = 210$ GeV, and ω_T with $M_{\omega_T} = 200$ (lower dotted), 210 (lower short-dashed), and 220 GeV (lower medium-dashed); $Q_U + Q_D = 0$ and $M_{\pi_T} = 110$ GeV.

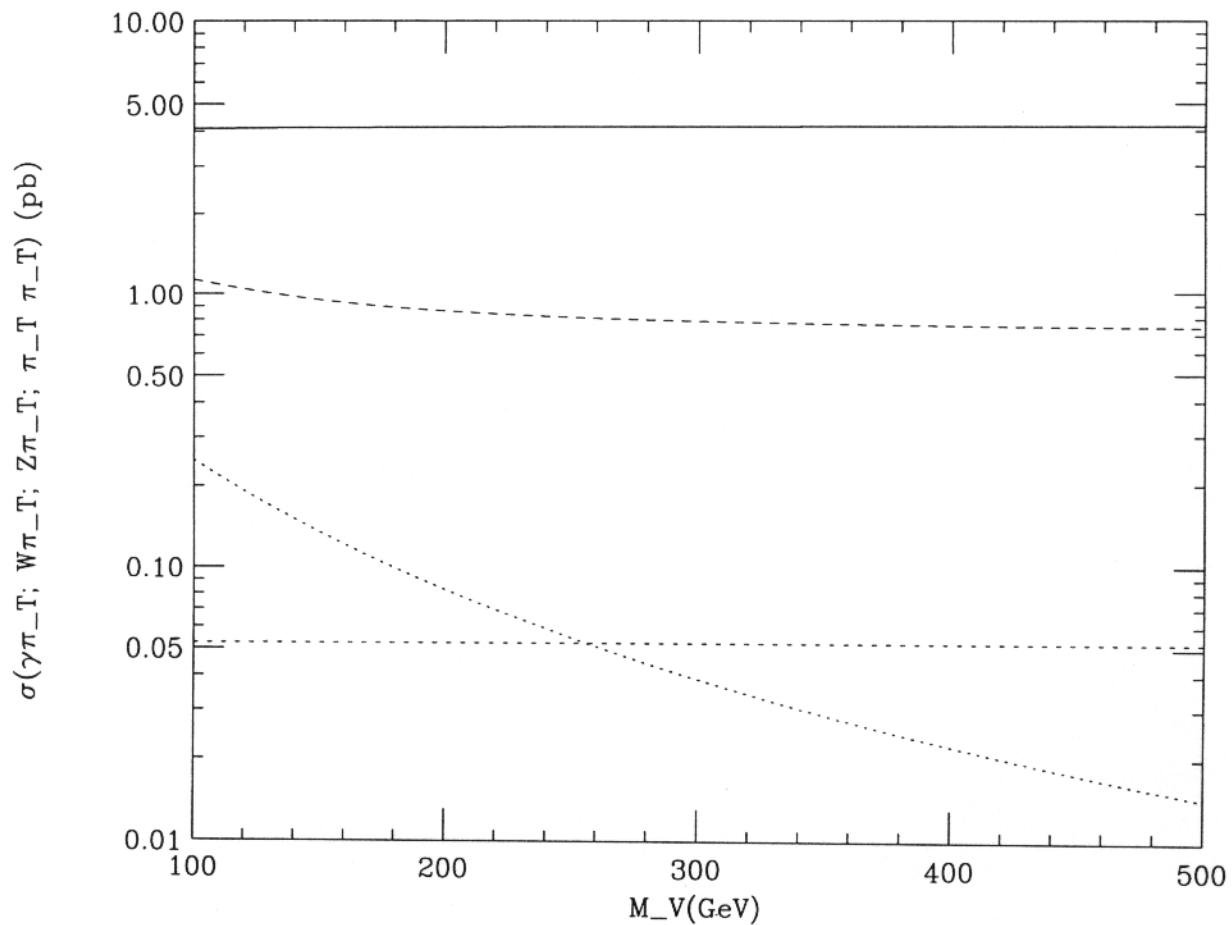


Figure 8: Production rates for ω_T , ρ_T^0 , $\rho_T^\pm \rightarrow W\pi_T$ (solid curve), $Z\pi_T$ (long-dashed), $\pi_T\pi_T$ (short-dashed) and $\gamma\pi_T$ (dotted) versus M_V , for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200-220$ GeV; $Q_U + Q_D = 0$ and $M_{\pi_T} = 110$ GeV.

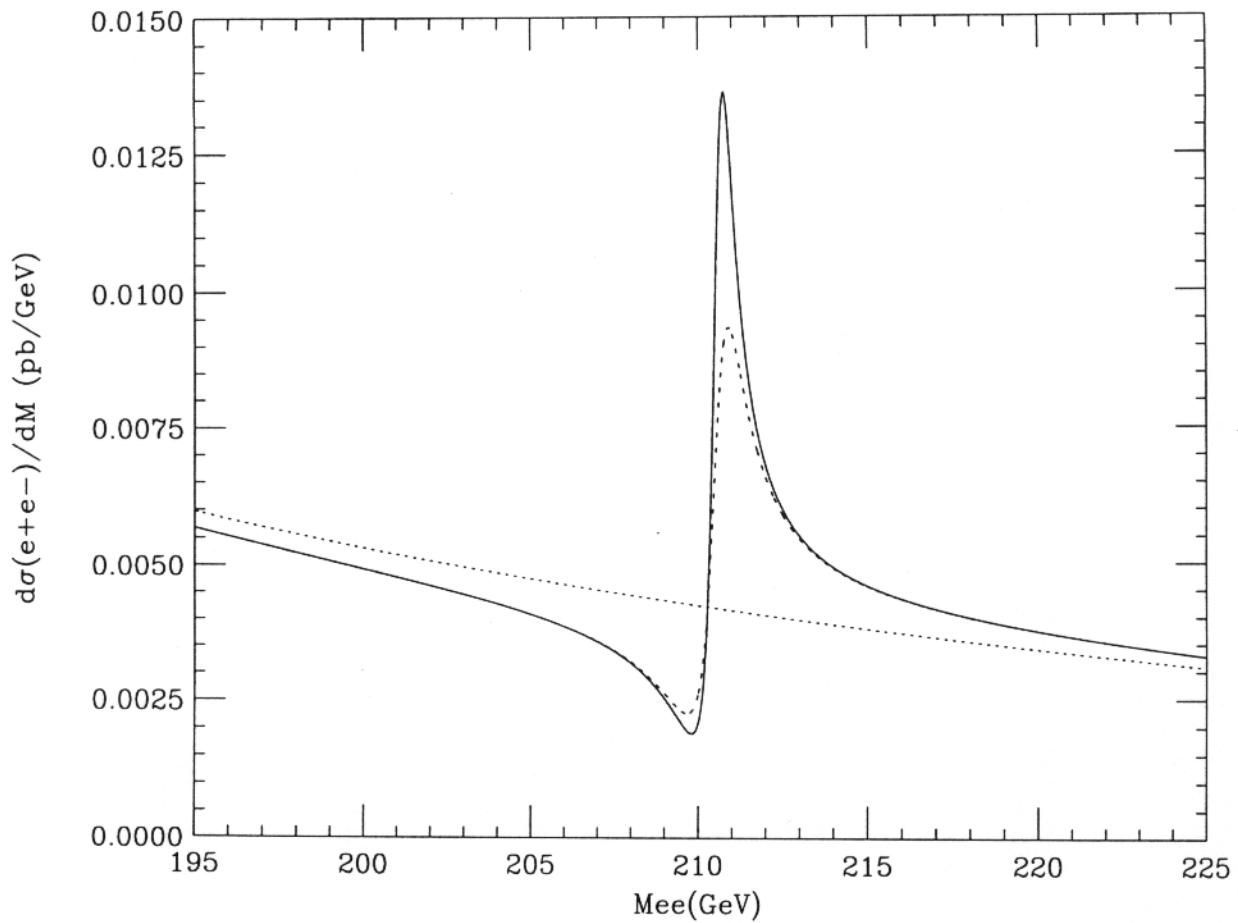


Figure 9: Invariant mass distributions for $\rho_T^0 \rightarrow e^+e^-$ for $M_{\rho_T} = 210$ GeV; $M_V = 100$ GeV (dashed curve) and 500 GeV (solid). The standard model background is the sloping dotted line. $Q_U + Q_D = 0$ and $M_{\pi_T} = 110$ GeV.

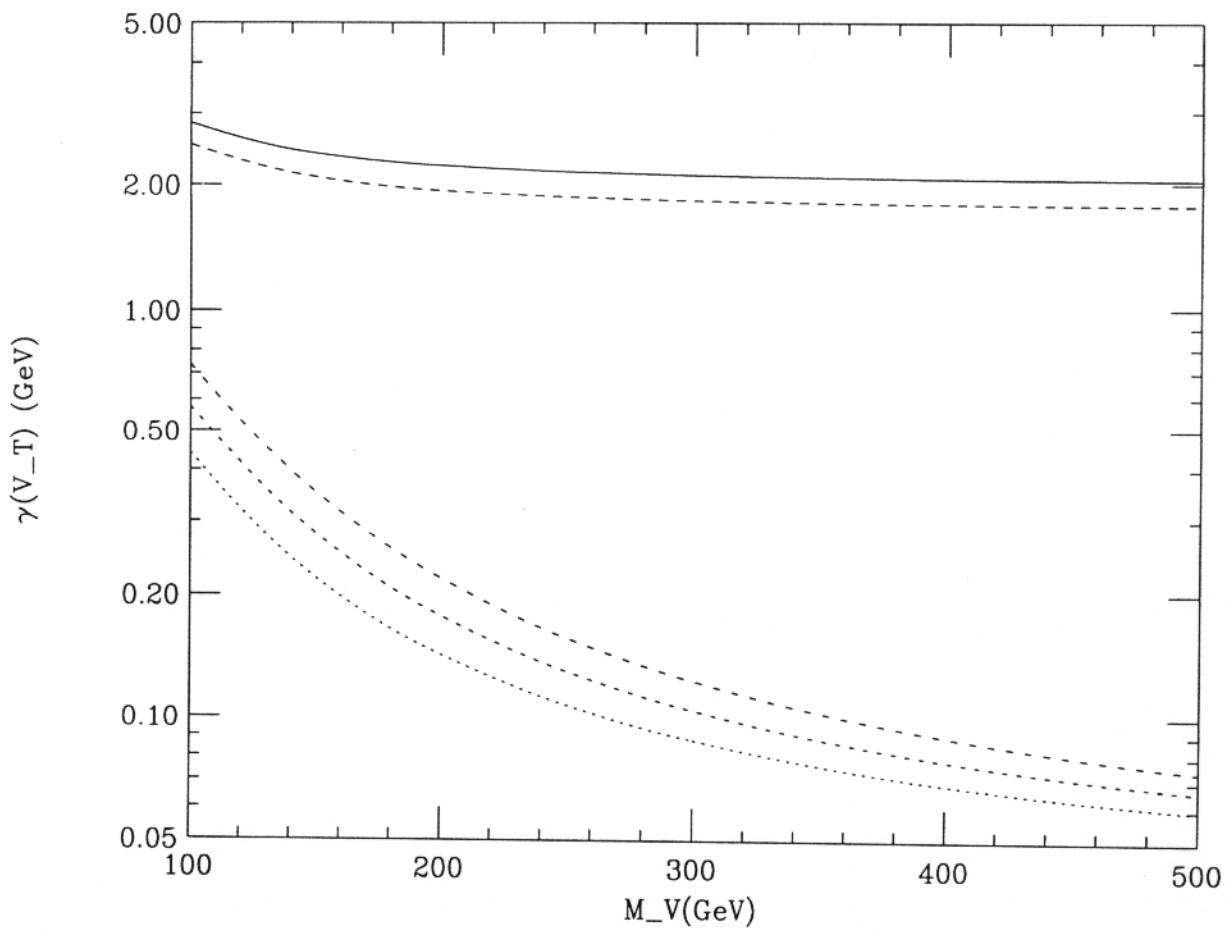


Figure 10: Technivector meson decay rates versus $M_V = M_A$ for ρ_T^0 (solid curve) and ρ_T^\pm (long-dashed) with $M_{\rho_T} = 210$ GeV, and ω_T with $M_{\omega_T} = 200$ (lower dotted), 210 (lower short-dashed), and 220 GeV (lower medium-dashed); $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 100$ GeV.

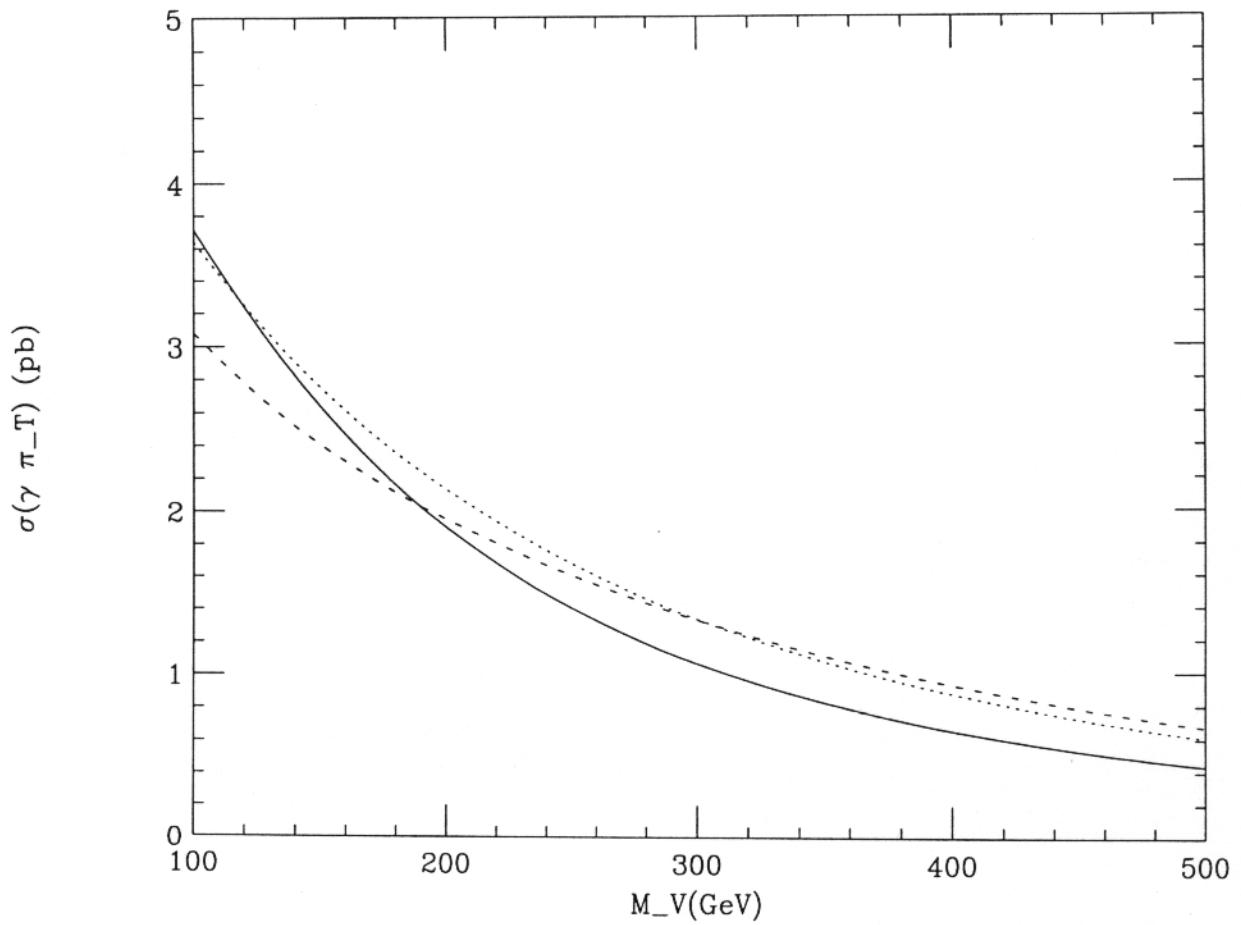


Figure 11: Production rates for the sum of ω_T , ρ_T^0 , $\rho_T^\pm \rightarrow \gamma\pi_T$ versus M_V , for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (dotted curve), 210 (solid), and 220 GeV (short-dashed); $Q_U + Q_D = 5/3$, and $M_{\pi_T} = 100$ GeV.

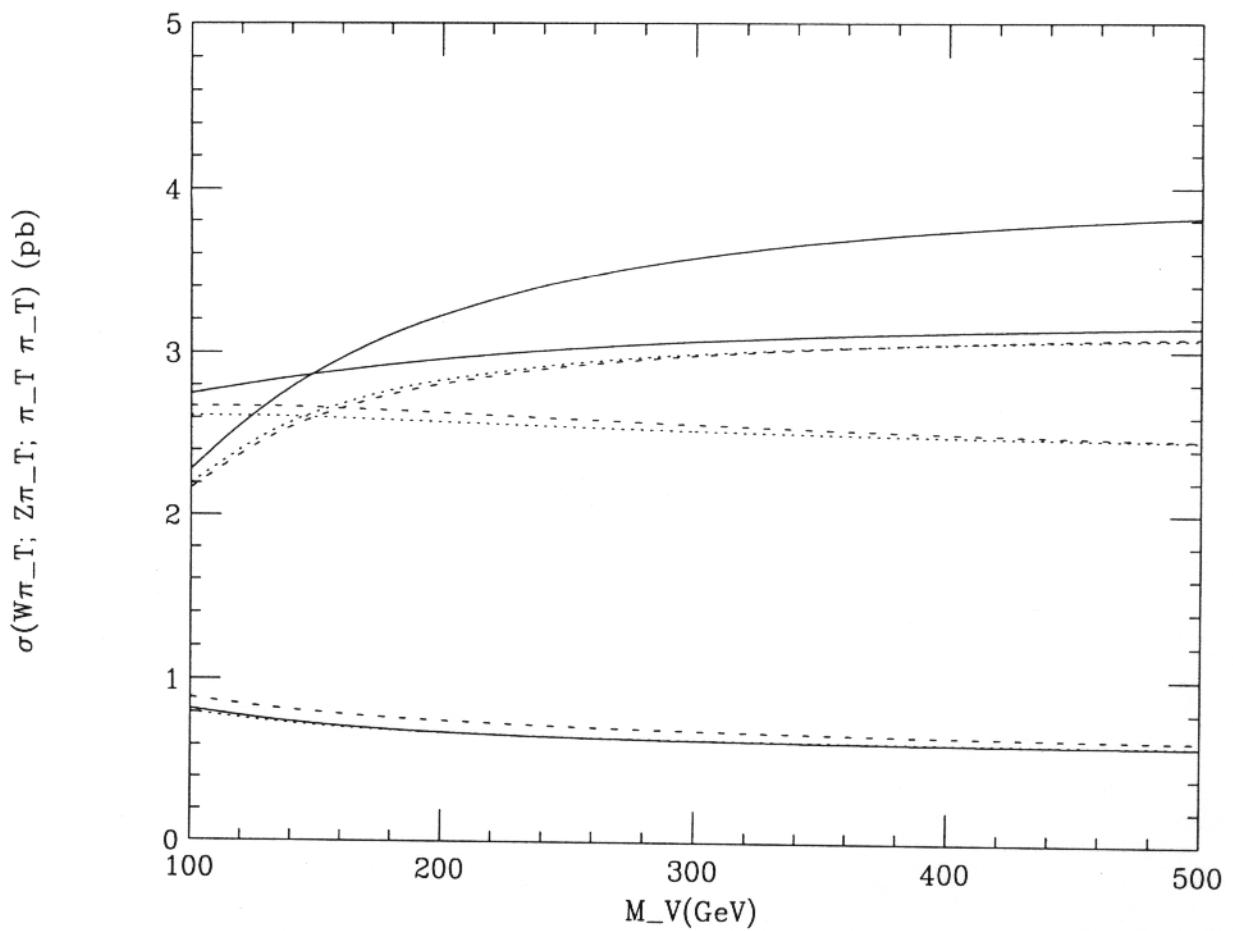


Figure 12: Production rates for ρ_T^0 , ρ_T^\pm , $\omega_T \rightarrow \pi_T \pi_T$ (three curves starting near 2.2), $W\pi_T$ (three curves starting near 2.6), and $Z\pi_T$ (lower curves) versus M_V , for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (dotted), 210 (solid), and 220 GeV (short-dashed); $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 100$ GeV.

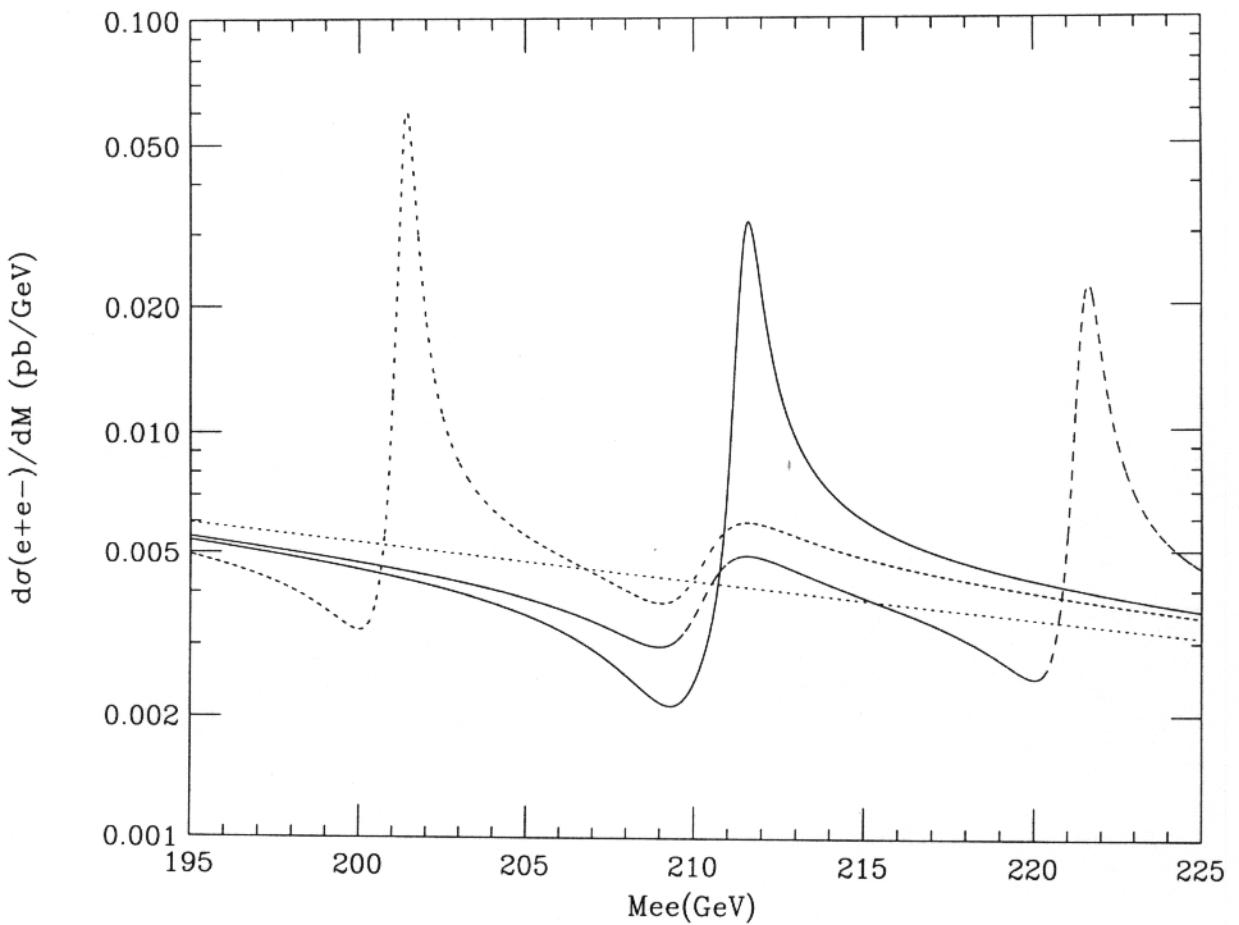


Figure 13: Invariant mass distributions for ω_T , $\rho_T^0 \rightarrow e^+e^-$ for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (short-dashed curve), 210 (solid), and 220 GeV (long-dashed); $M_V = 100$ GeV. The standard model background is the sloping dotted line. $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 100$ GeV.

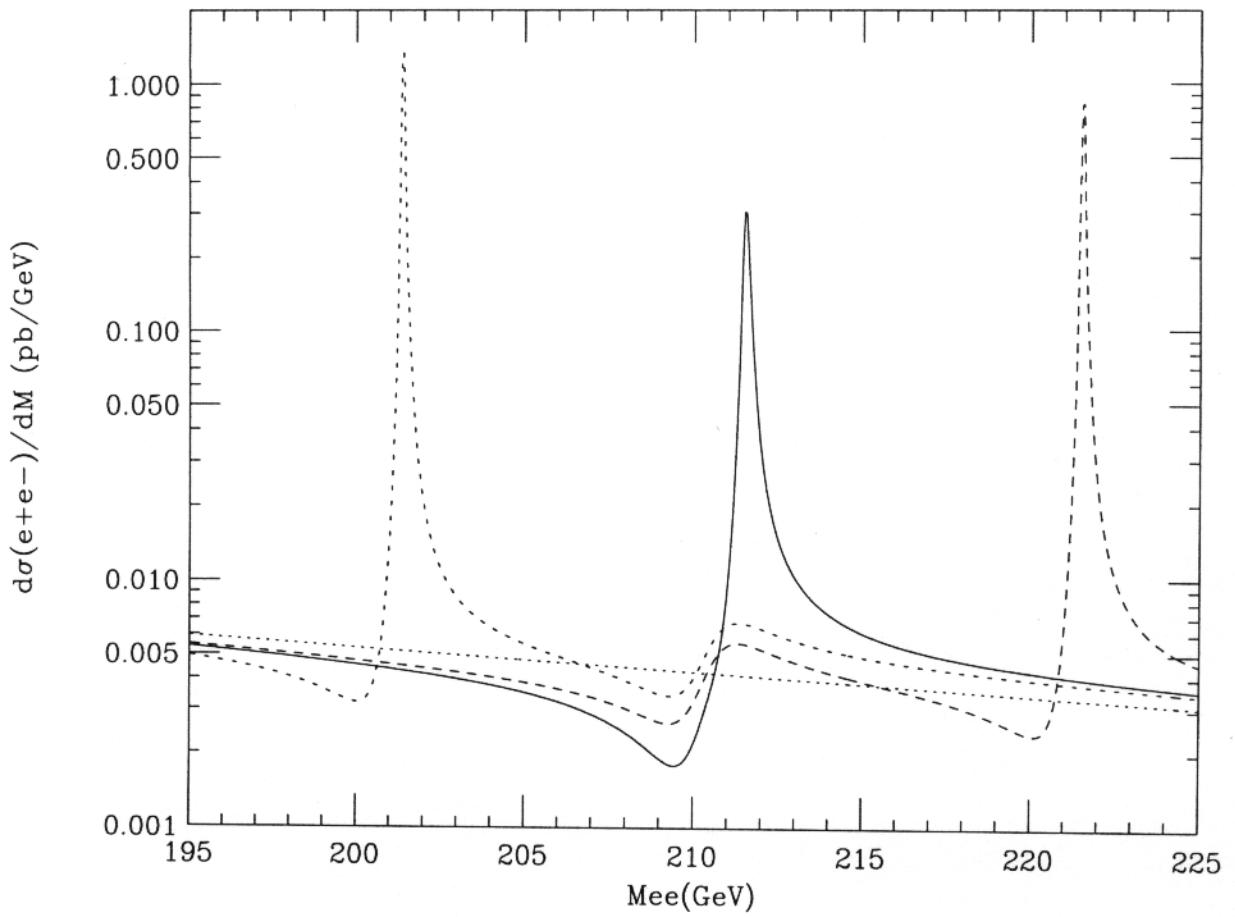


Figure 14: Invariant mass distributions for ω_T , $\rho_T^0 \rightarrow e^+e^-$ for $M_{\rho_T} = 210$ GeV and $M_{\omega_T} = 200$ (short-dashed curve), 210 (solid), and 220 GeV (long-dashed); $M_V = 500$ GeV. The standard model background is the sloping dotted line. $Q_U + Q_D = 5/3$ and $M_{\pi_T} = 100$ GeV.

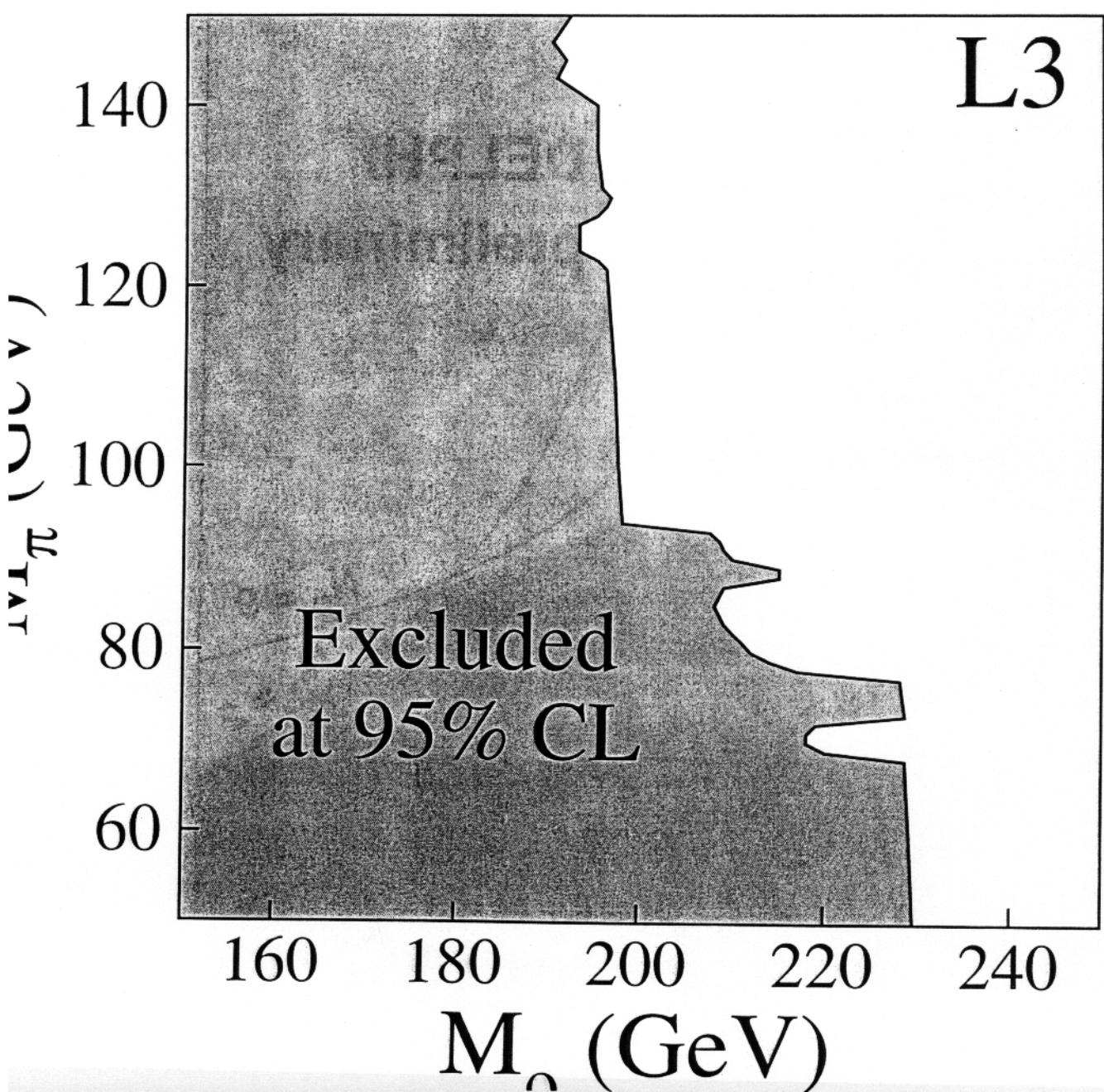
III.4 EXPERIMENTAL SEARCHES

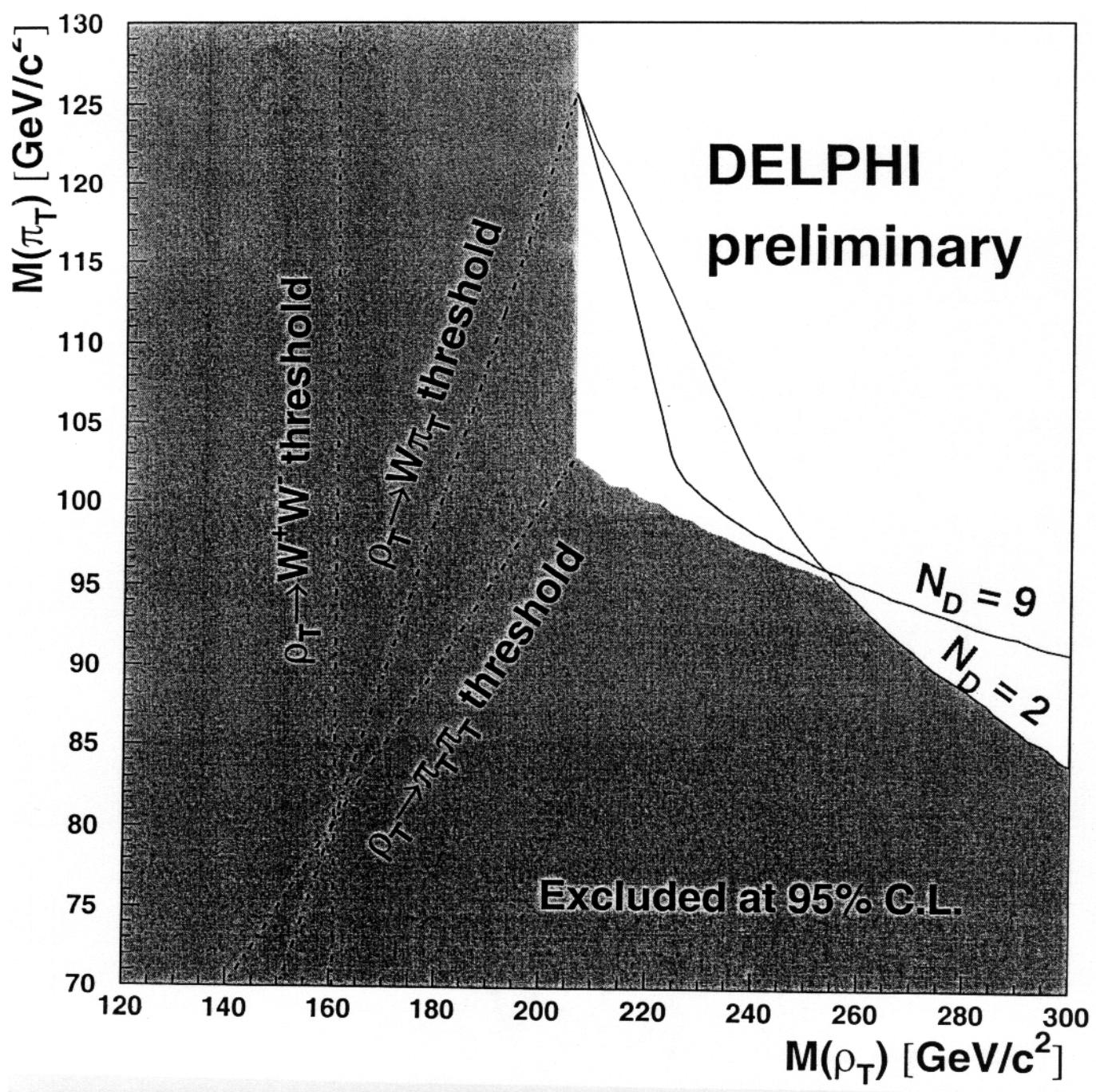
III.4a Color-Singlet TCSM Modes

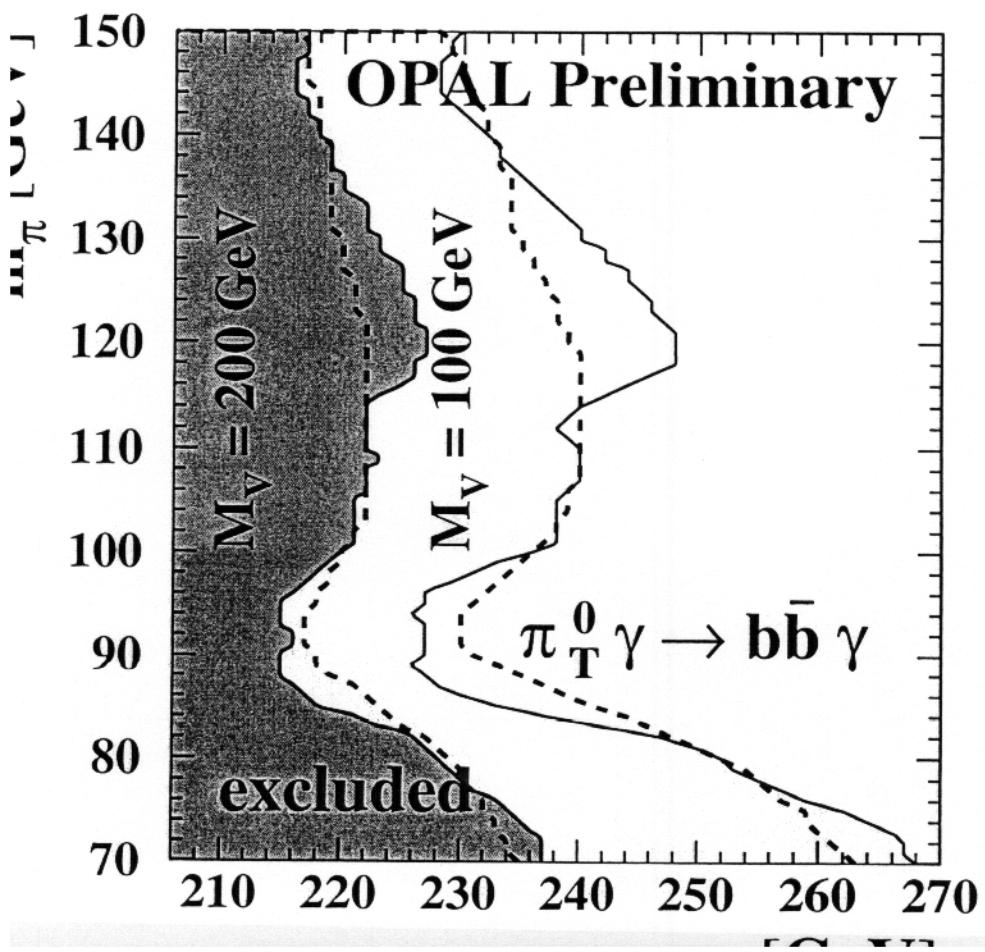
1. L3 exclusion plot. $\int \mathcal{L} dt = 176 \text{ pb}^{-1}$ at $\langle \sqrt{s} \rangle = 189 \text{ GeV}$; $M_V = M_A = 200 \text{ GeV}$ and $Q_U + Q_D = 5/3, 0, -1$.
2. DELPHI exclusion plot for $\sqrt{s} = 161 - 202 \text{ GeV}$ (does not use $\rho_T, \omega_T \rightarrow \gamma\pi_T^0, \gamma\pi_T^{0'}$ but does use $\rho_T \rightarrow W^+W^-$).
3. CDF $\rho_T \rightarrow W\pi_T \rightarrow \ell^\pm\nu_\ell b$ jet Run I data.
4. CDF $\rho_T \rightarrow W\pi_T$ exclusion plot (based on an obsolete TCSM).
5. CDF $\rho_T \rightarrow W\pi_T$ Run II exclusion plots.
6. CDF $\rho_T, \omega_T \rightarrow \gamma\pi_T \rightarrow \gamma b$ jet Run I data.
7. CDF $\rho_T, \omega_T \rightarrow \gamma\pi_T$ exclusion plot (based on an obsolete TCSM).
8. OPAL exclusion plots for $\sqrt{s} = 200 - 209 \text{ GeV}$ and $\int \mathcal{L} dt = 209 \text{ pb}^{-1}$. Default TCSM parameters with $M_V = 100$ and 200 GeV are used.
9. DØ $\rho_T, \omega_T \rightarrow e^+e^-$ exclusion plot from Run I data.
10. DØ $\rho_T, \omega_T \rightarrow e^+e^-$ Run II exclusion plot.

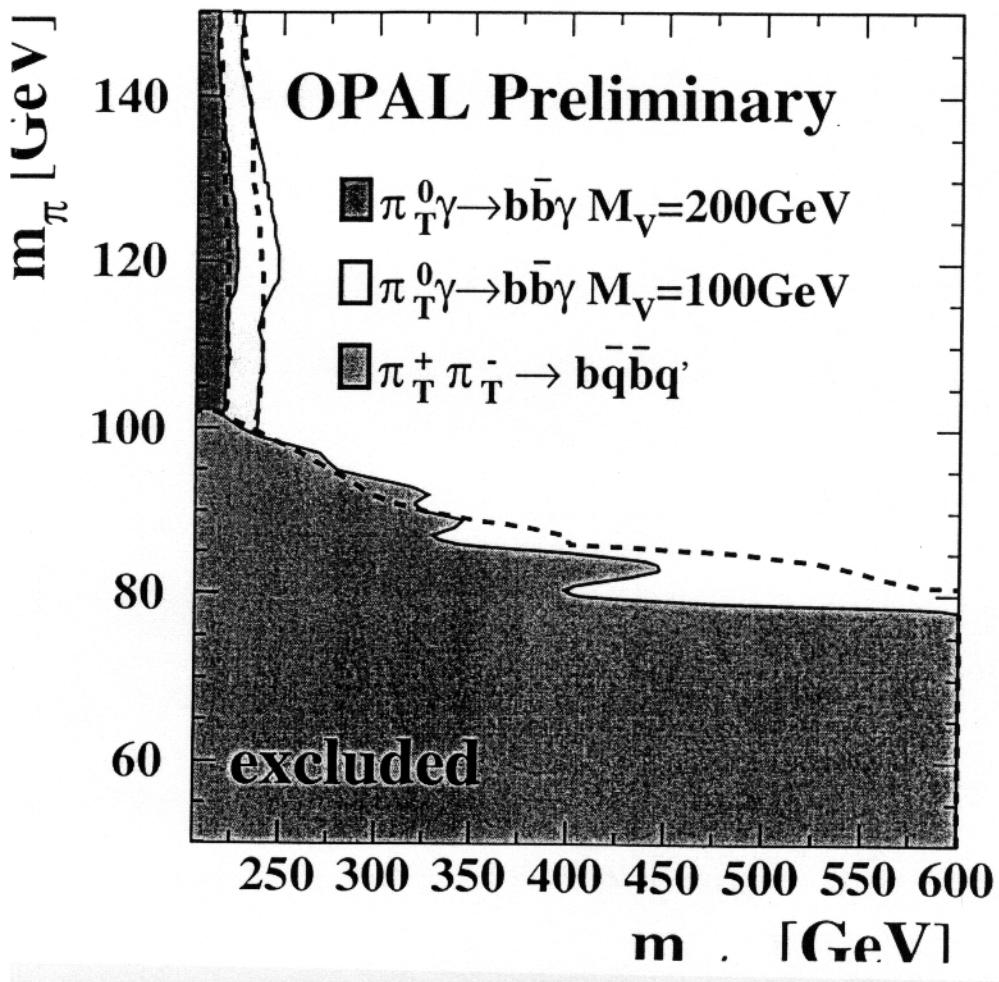
III.4b Color–Nonsinglet TCSM Modes

1. Searches to date.
2. CDF $\rho_{T8} \rightarrow \pi_{\bar{L}Q}\pi_{\bar{Q}L} \rightarrow \tau^+\tau^-jj$ exclusion plot.
3. CDF $\rho_{T8} \rightarrow jj$ exclusion plot.

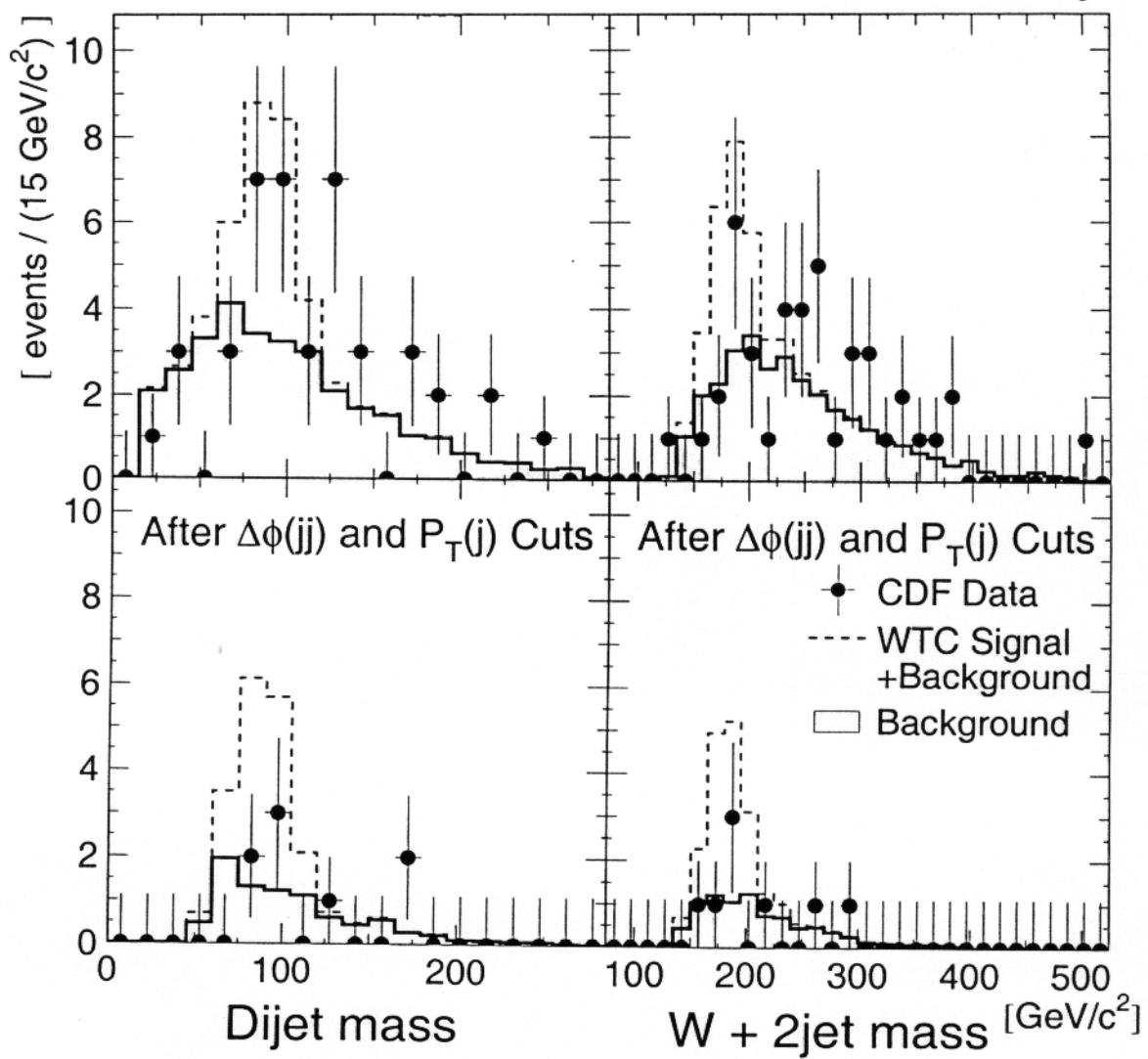


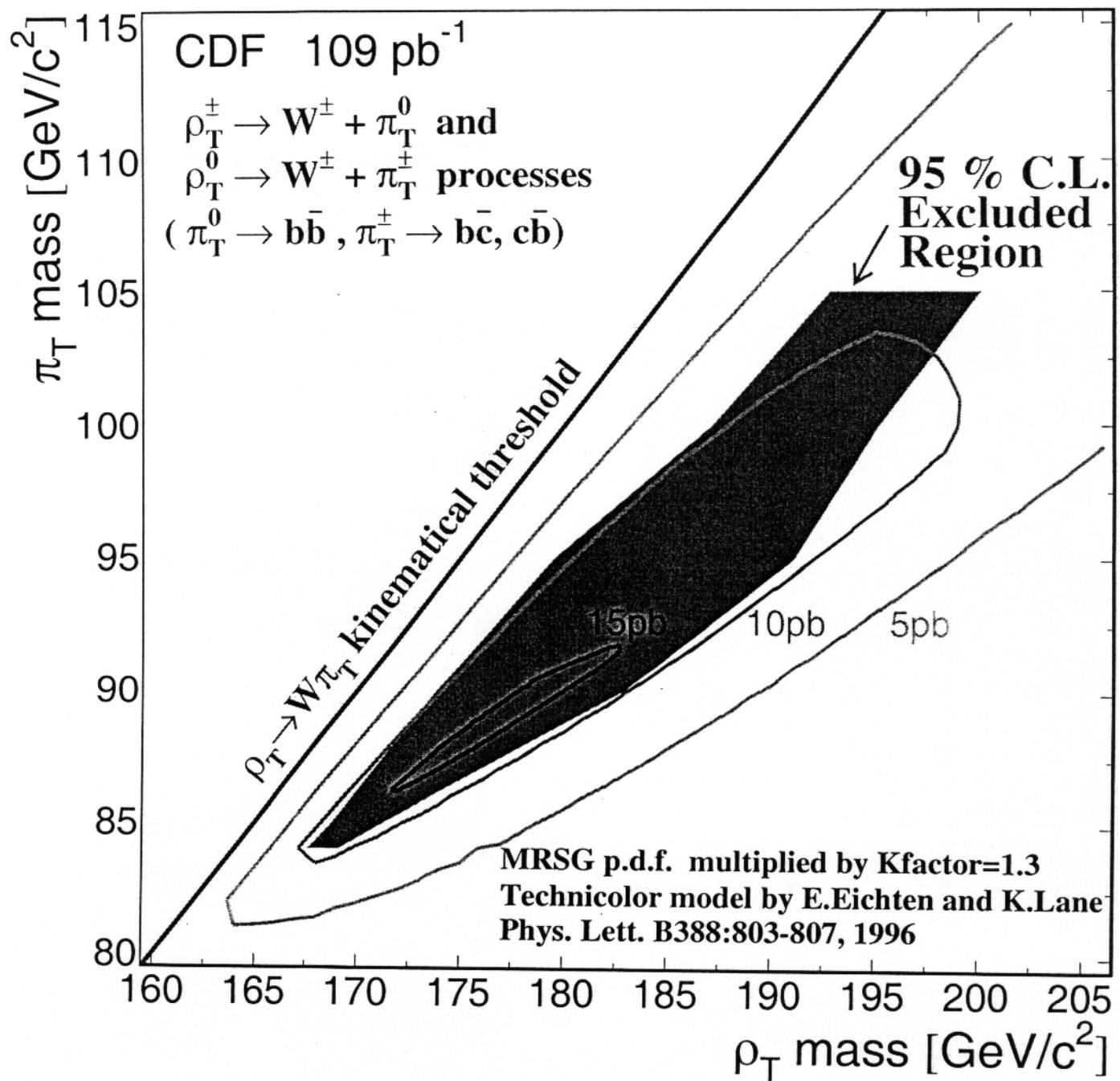




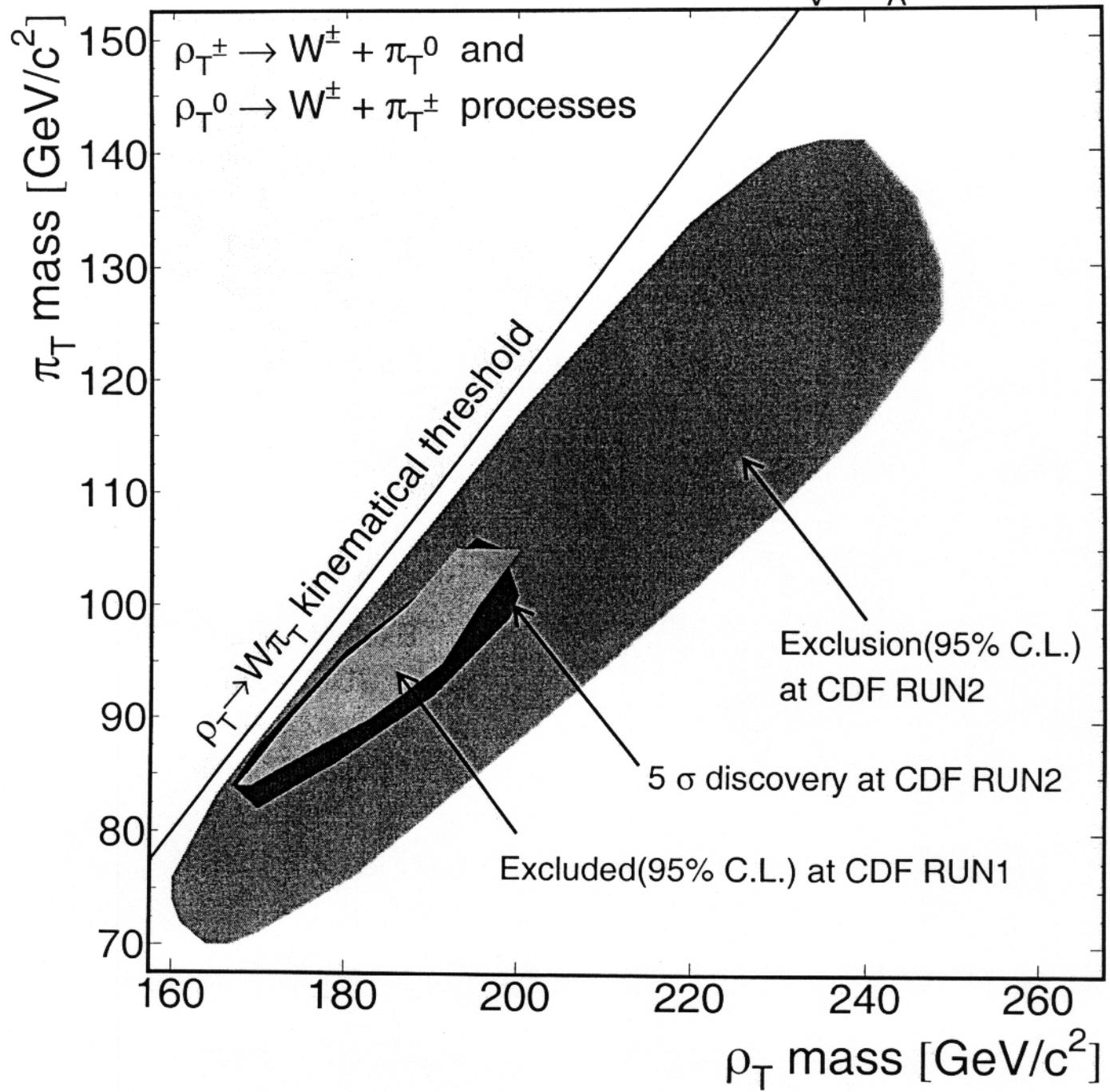


CDF Preliminary

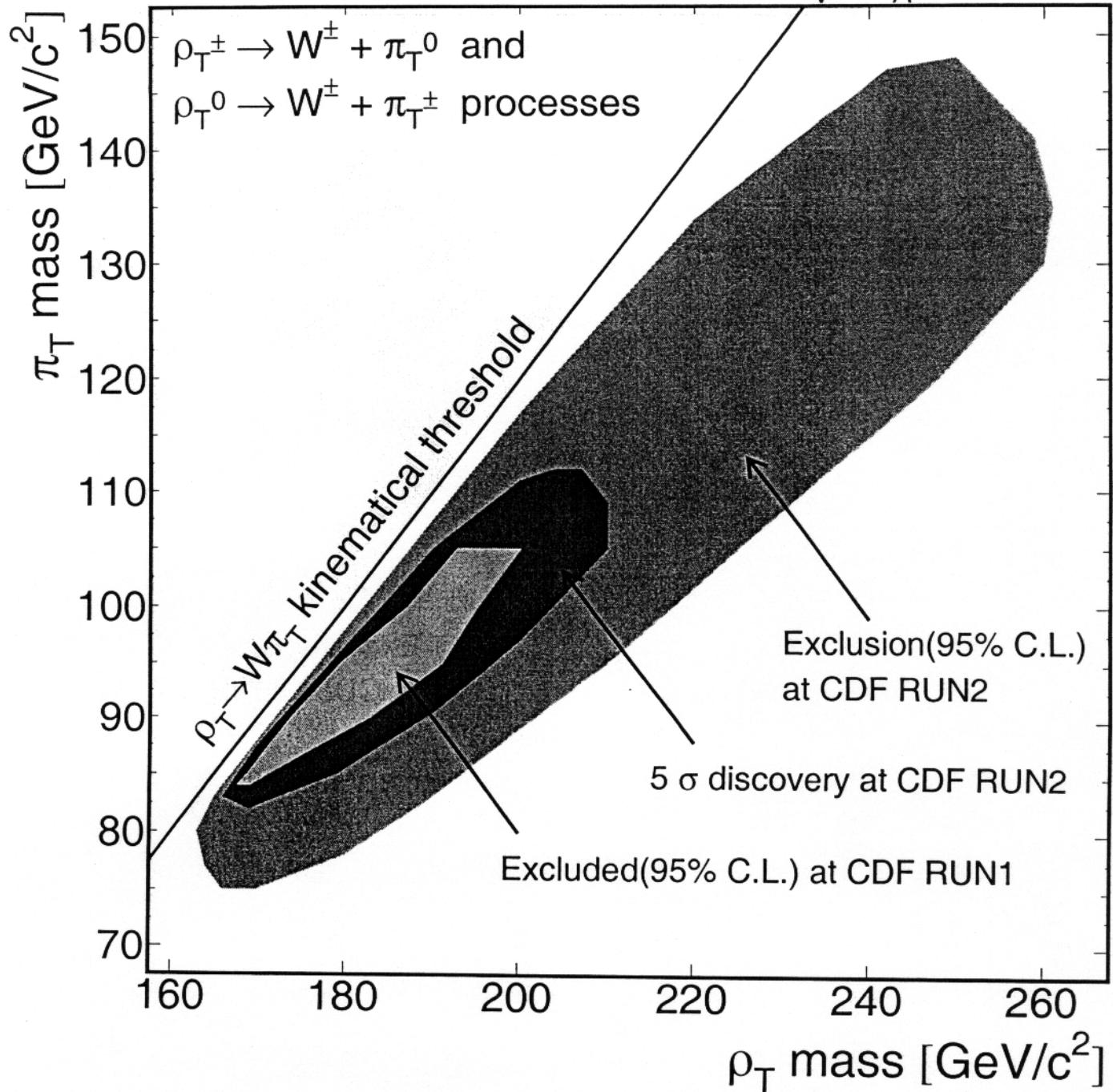




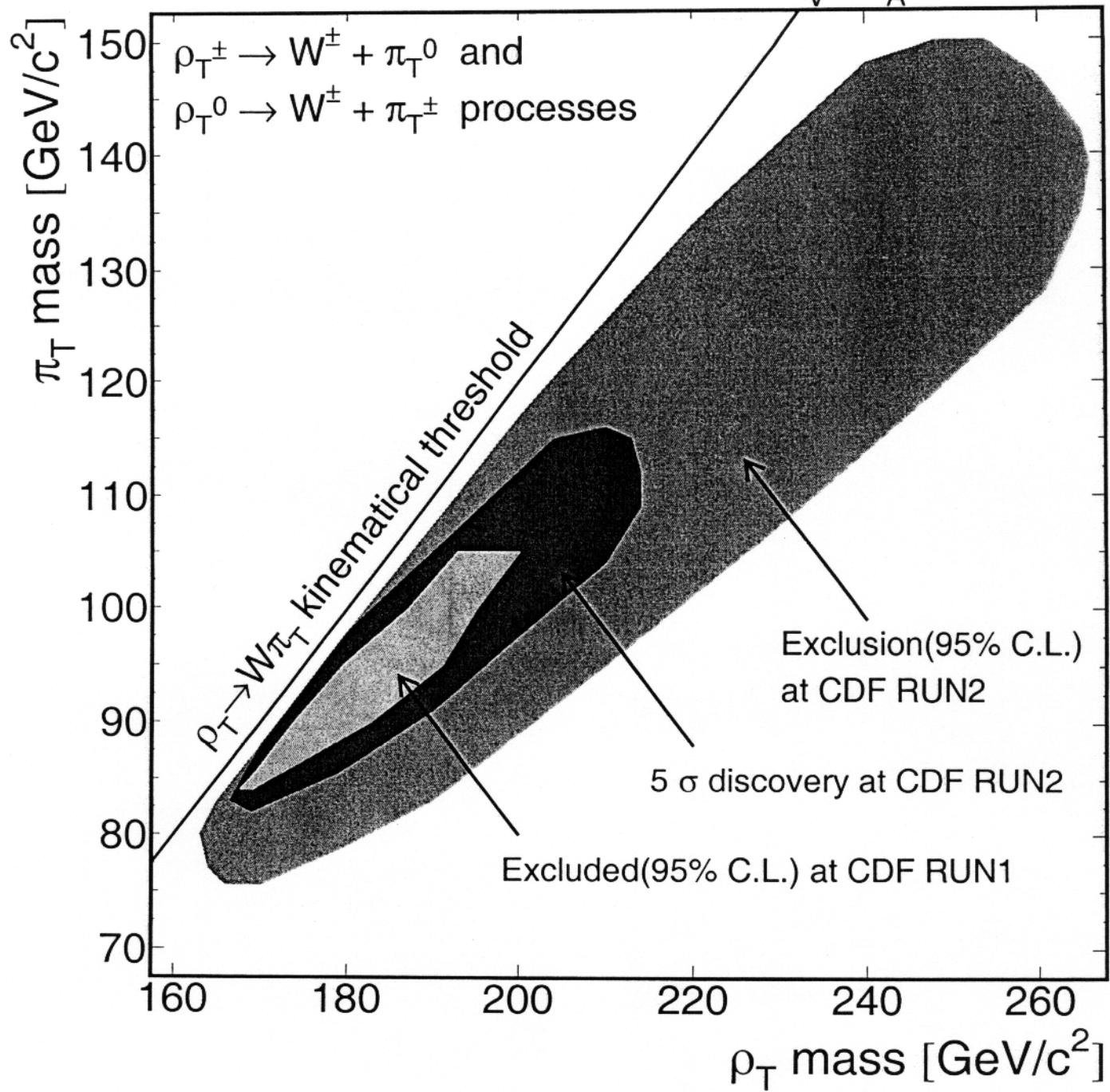
PYTHIA v6.139 : $M_V=M_A=100$ GeV

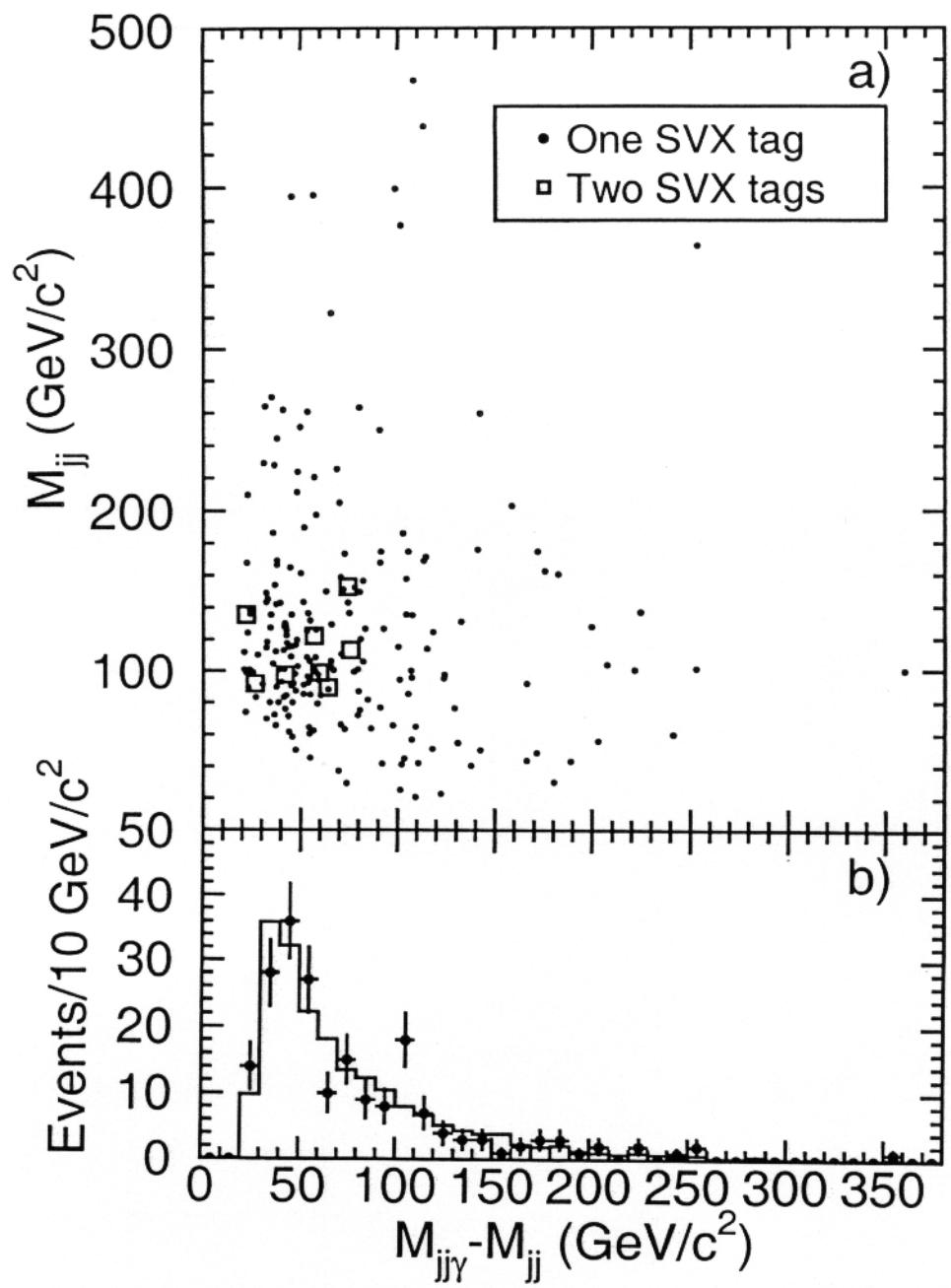


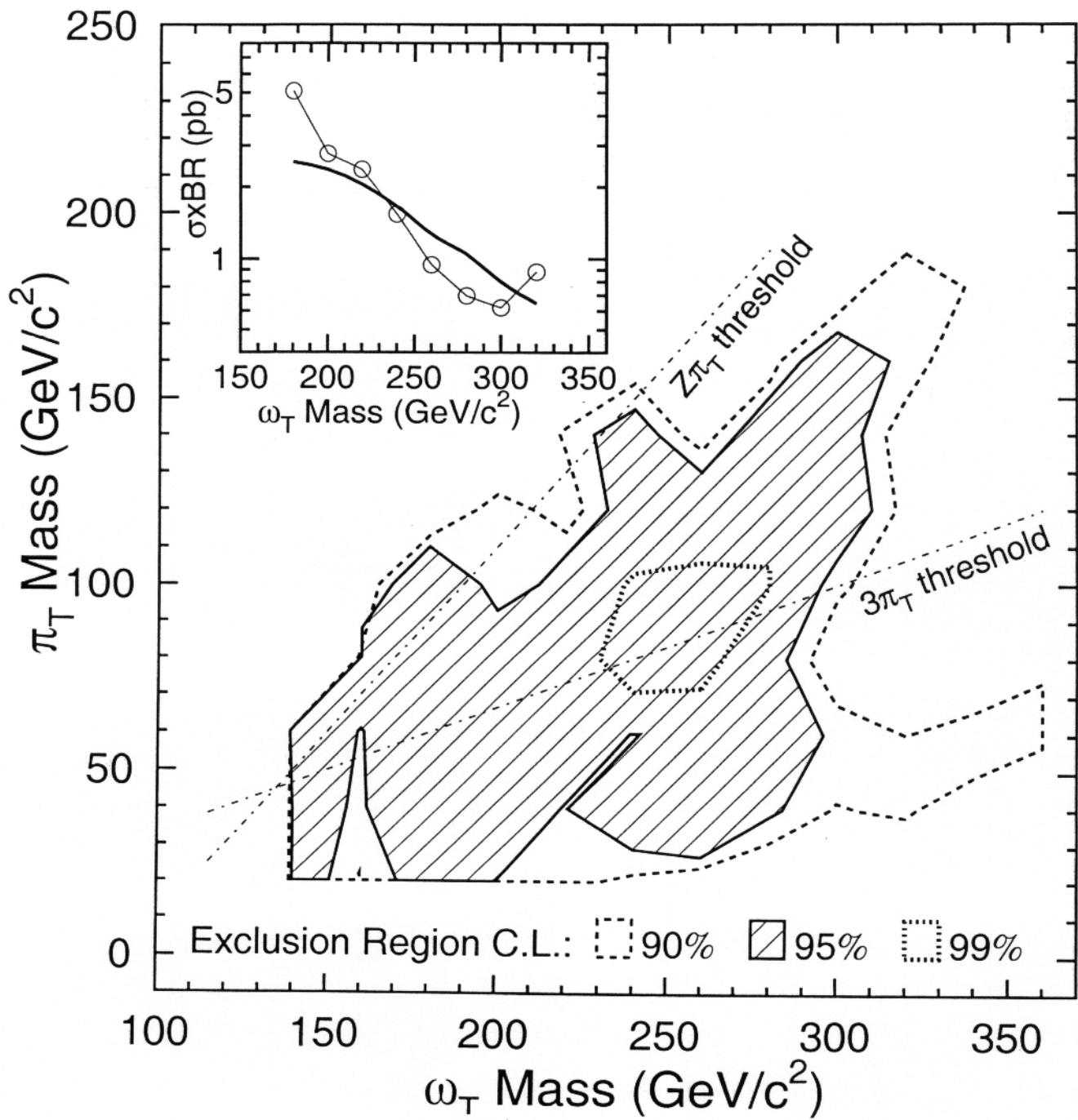
PYTHIA v6.139 : $M_V=M_A=200$ GeV

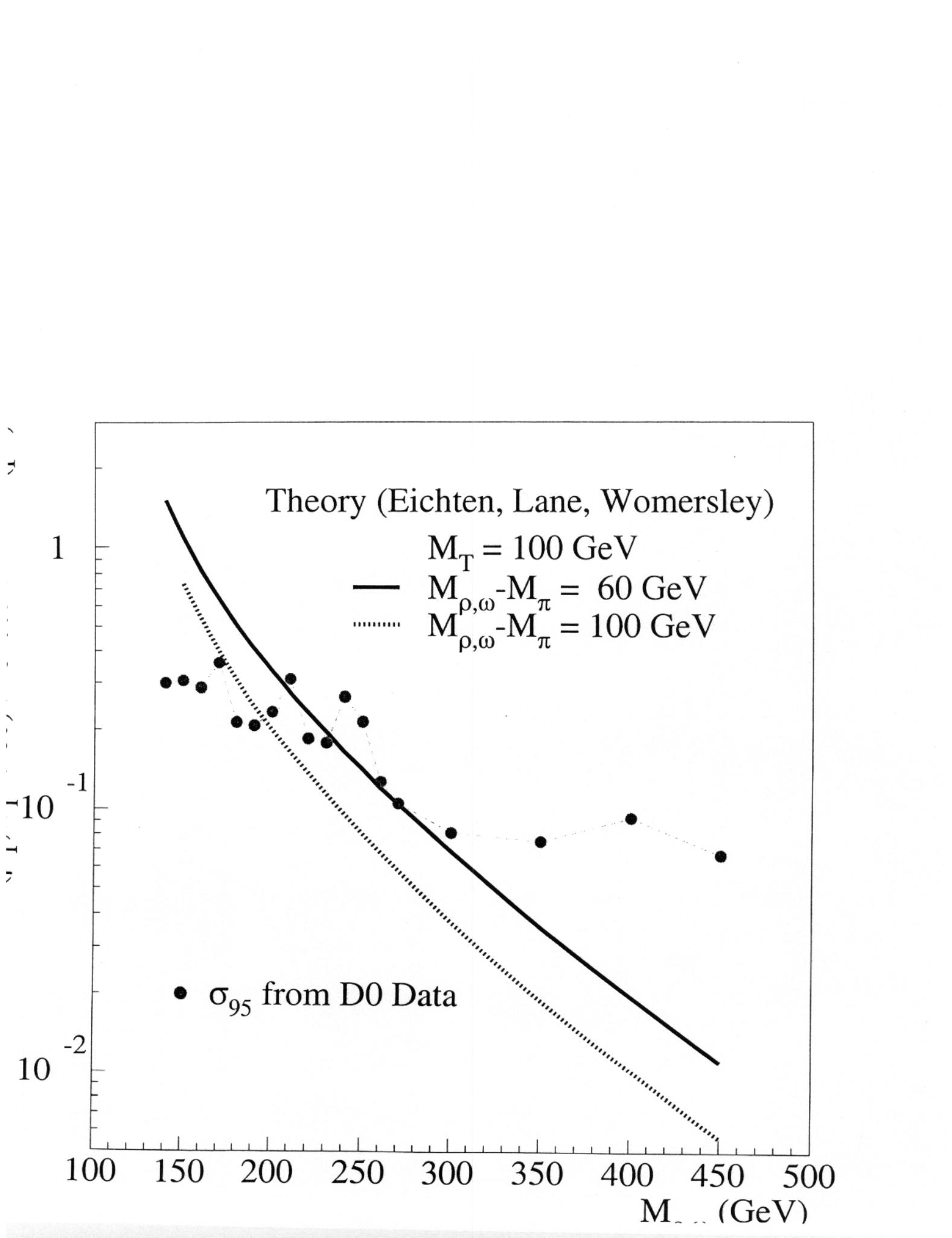


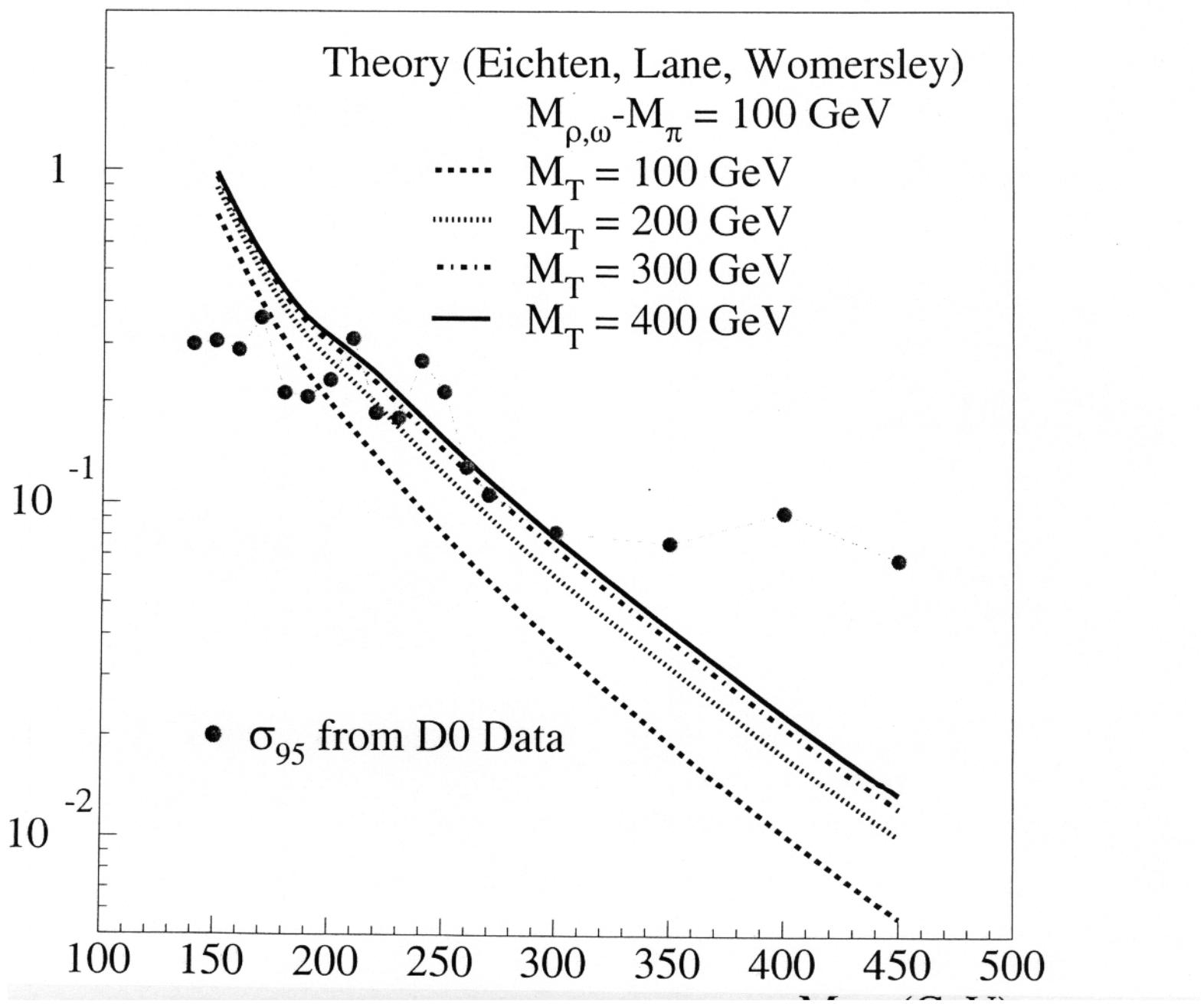
PYTHIA v6.139 : $M_V=M_A=400$ GeV

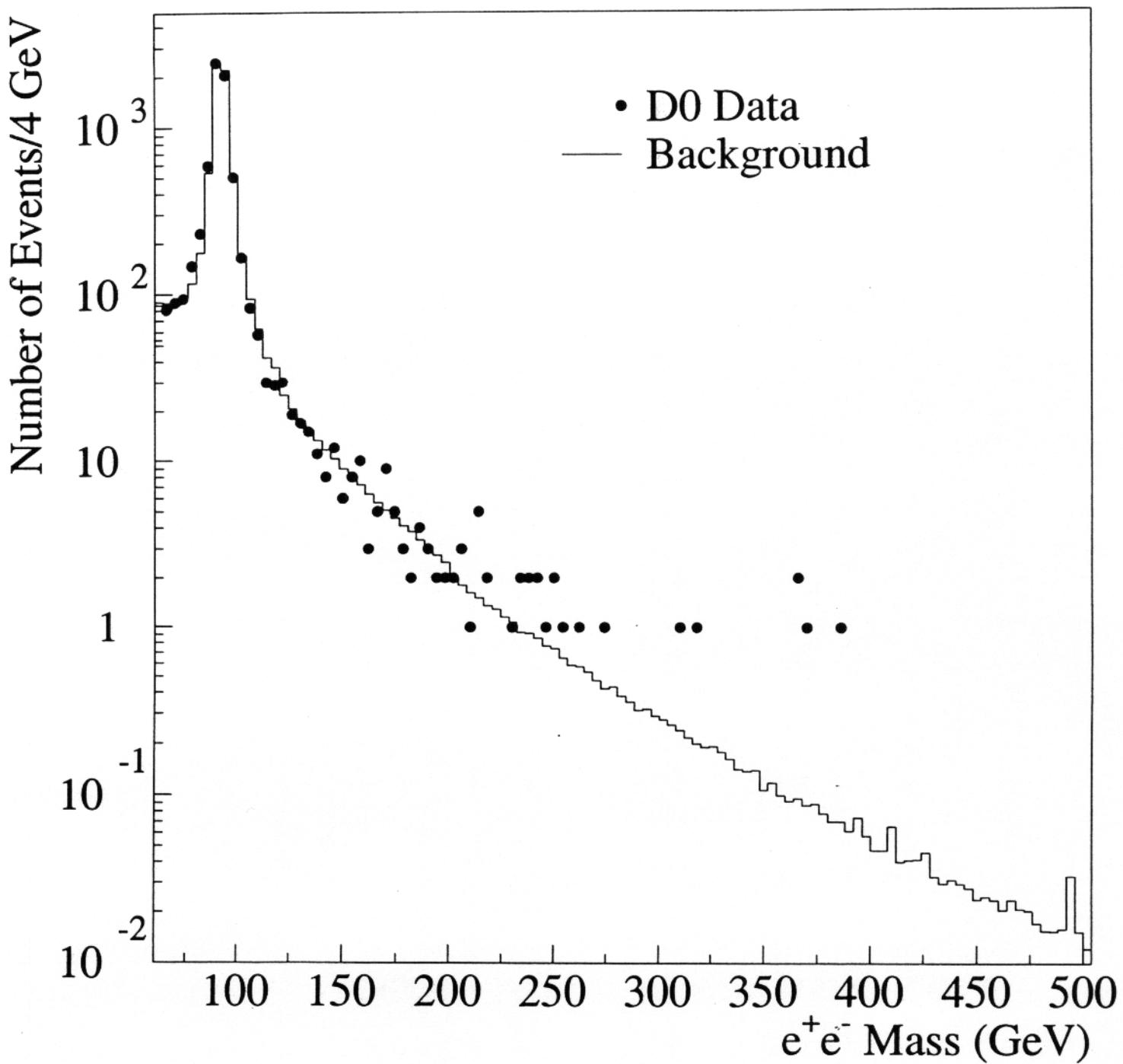




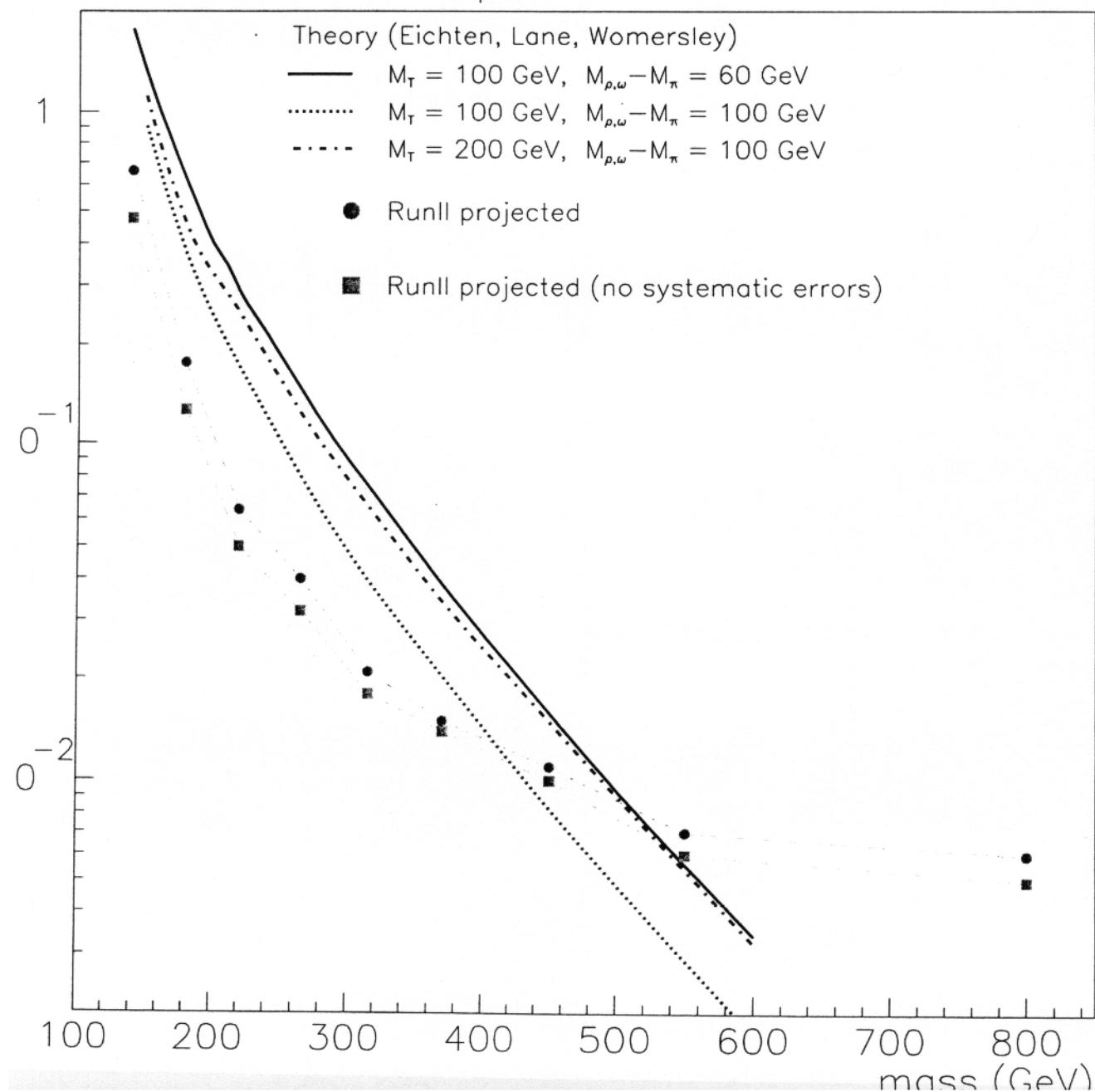


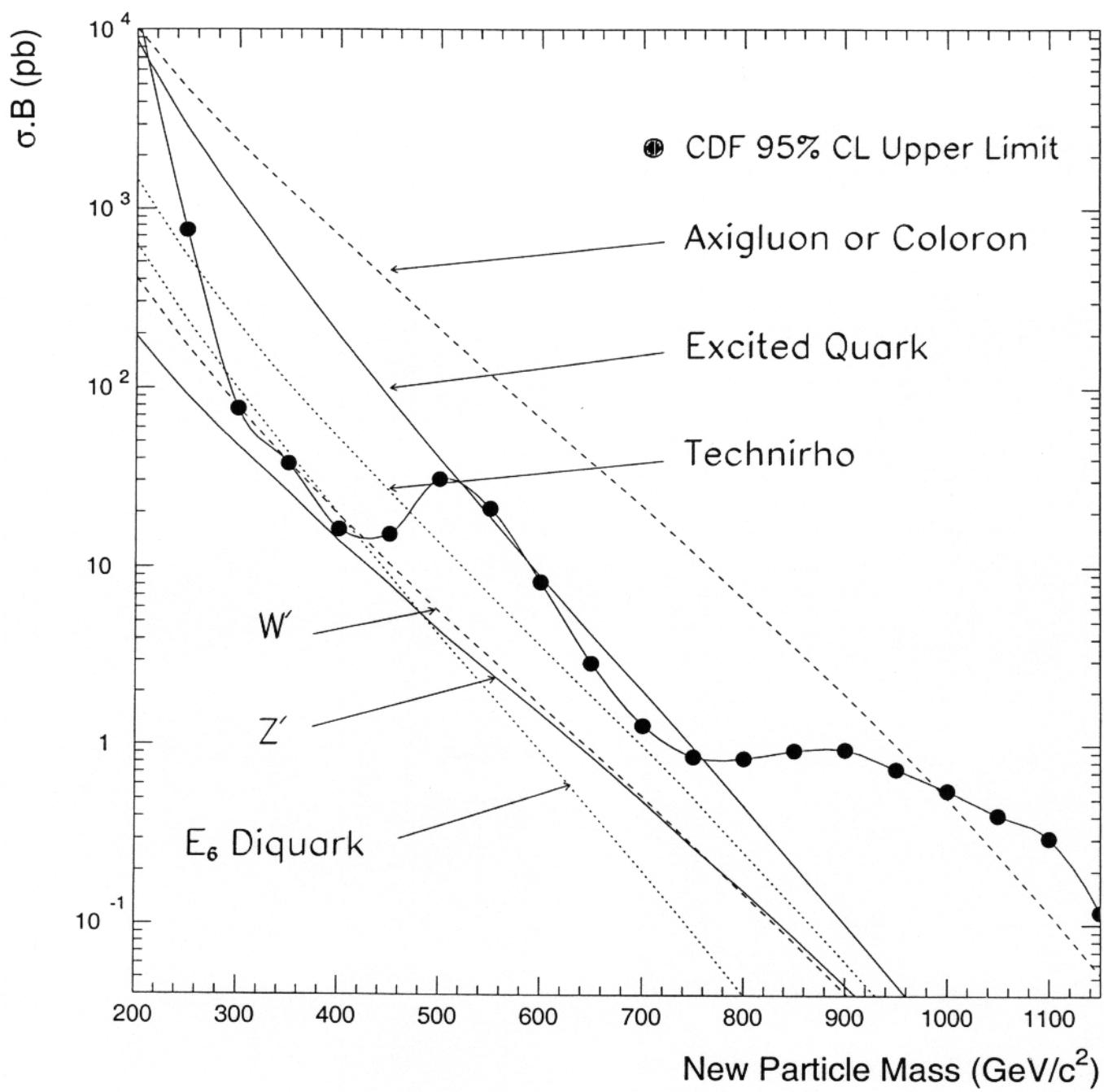


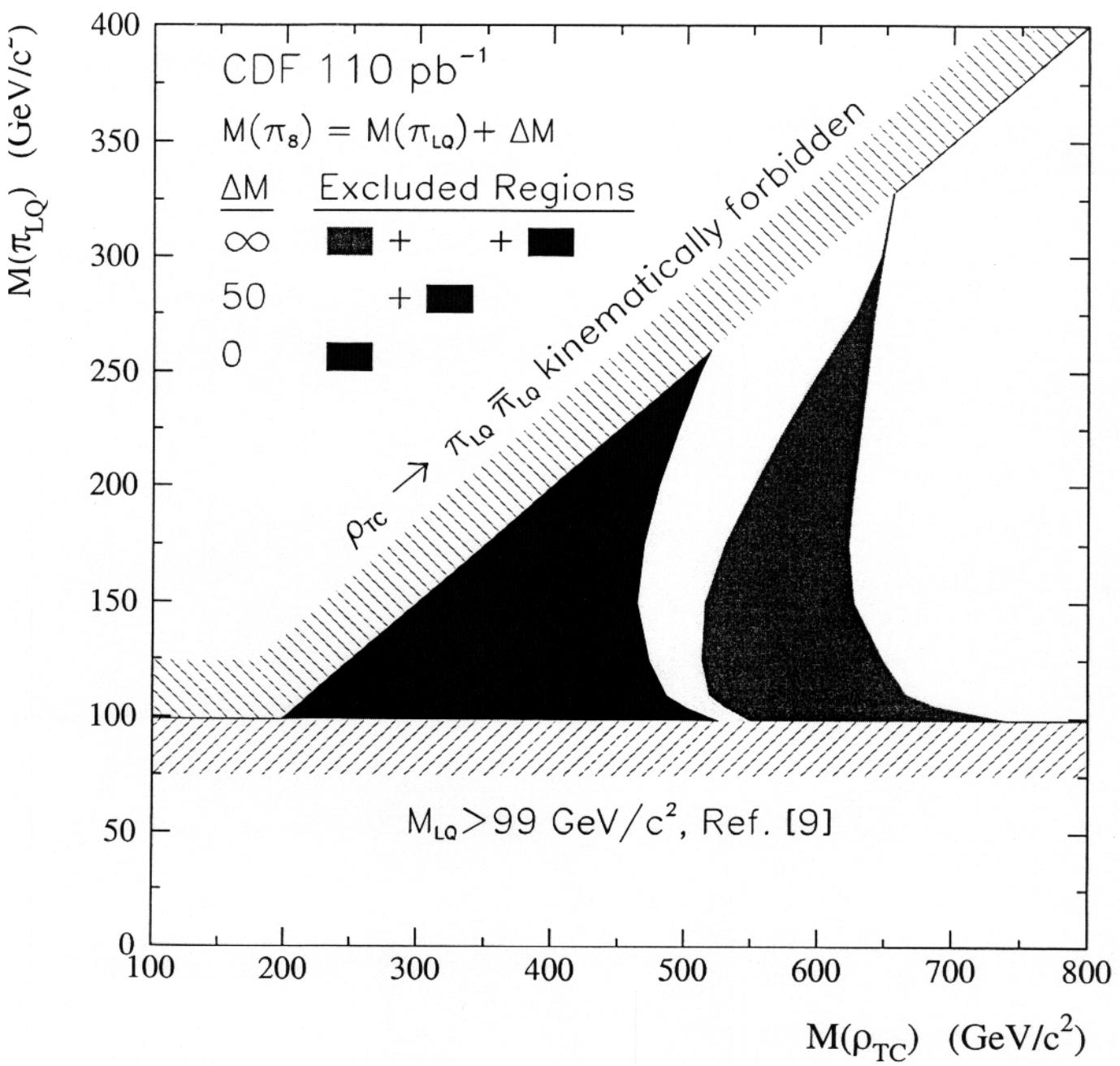


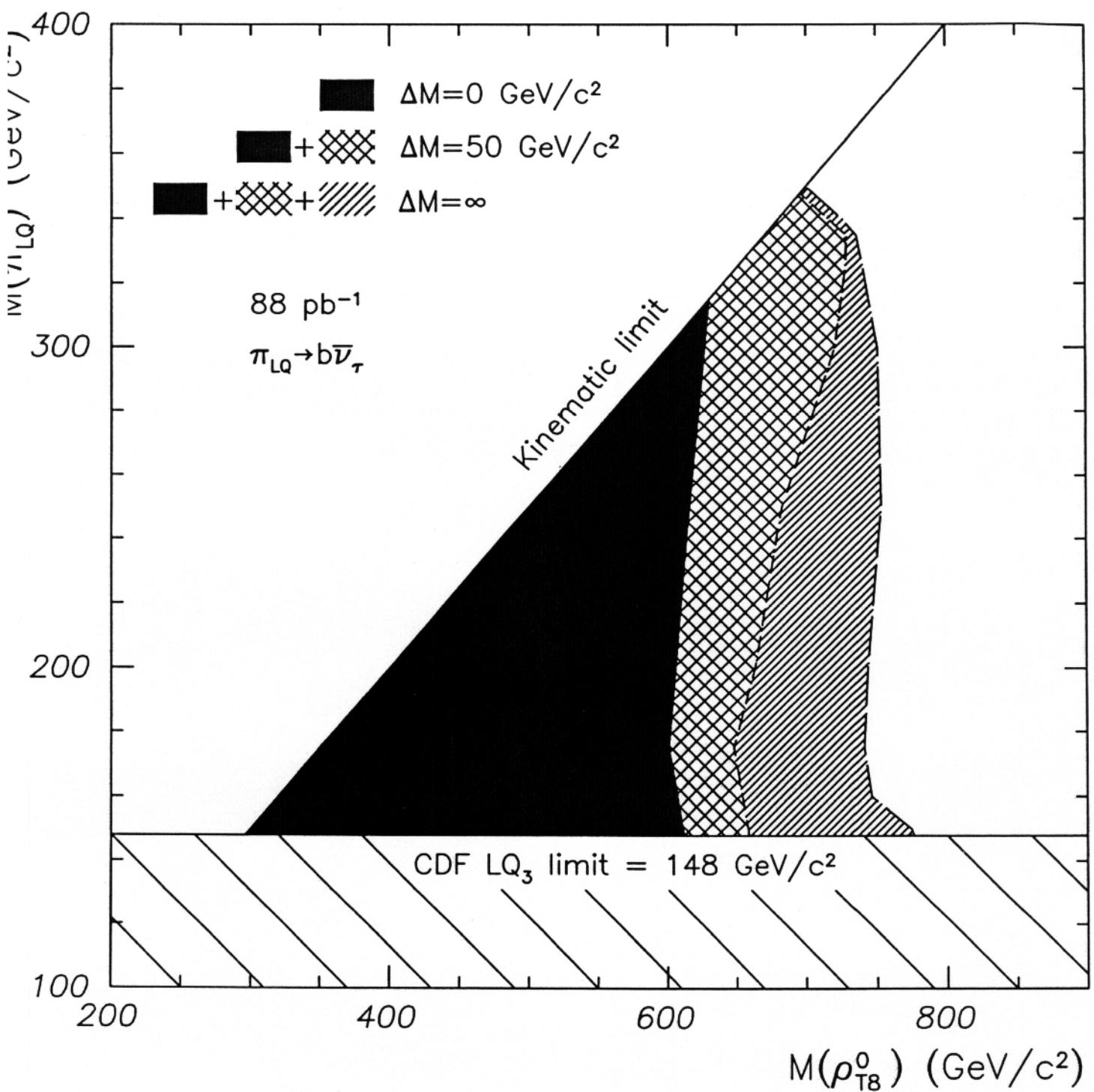


Expected Run II Limits









“Faith” is a fine invention
When Gentlemen can see —
But *Microscopes* are prudent
In an Emergency.

— Emily Dickinson, 1860